Searches for Higgs Bosons at the Tevatron

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For the CDF and DØ Collaborations

Outline:

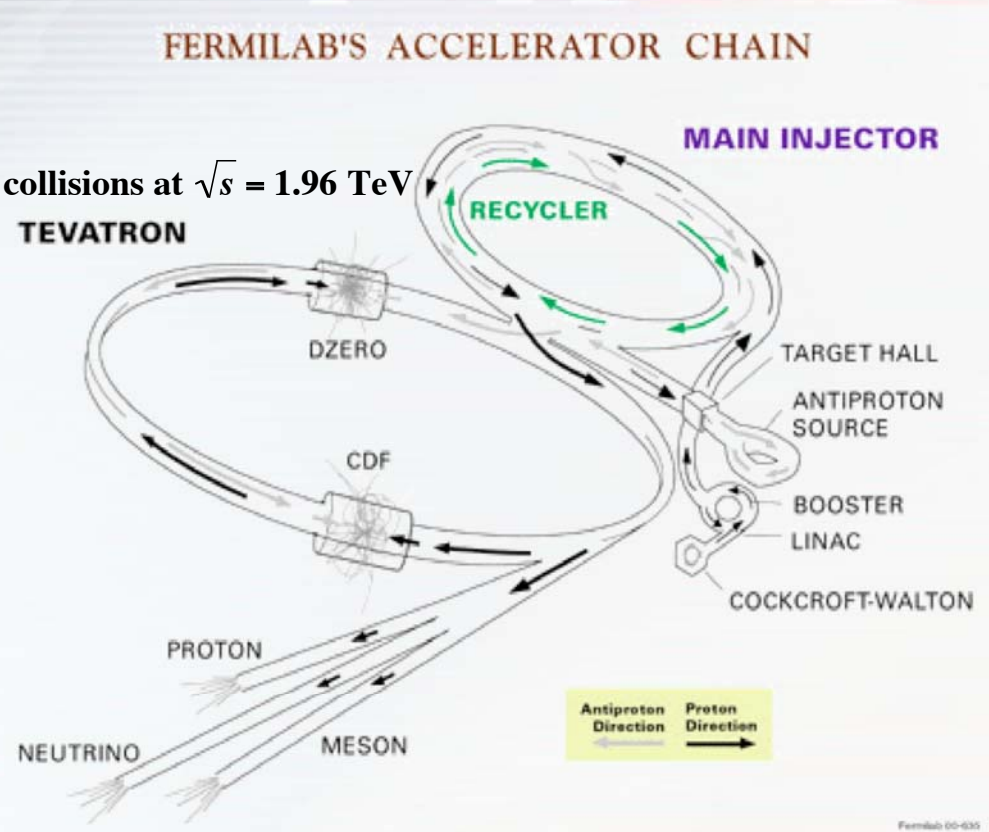
- **Direct Higgs searches at CDF and D0**
  - **SM Higgs**
  - **MSSM Higgs: Neutral, Charged**
  - **Doubly-charged Higgs**
- **Near future prospects**

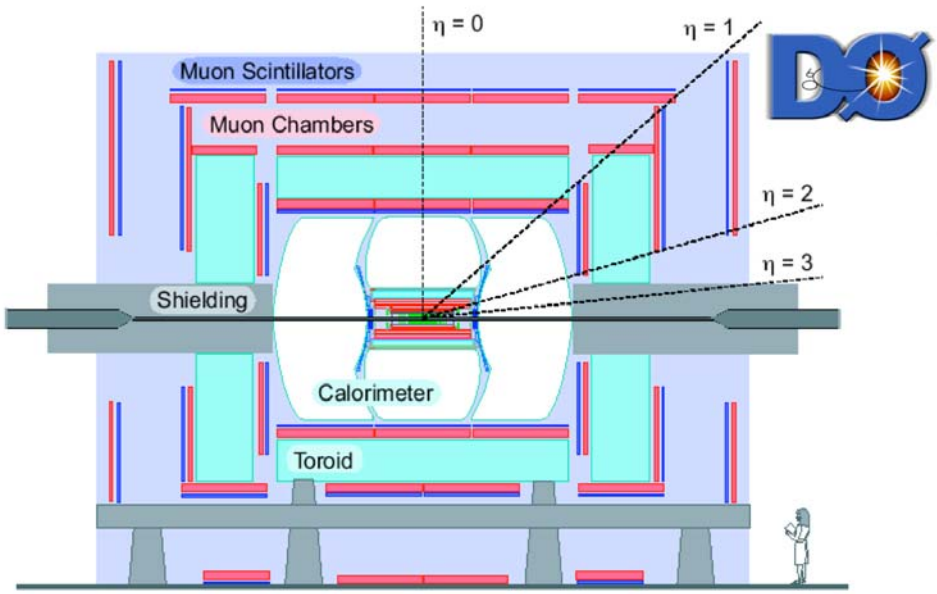
SUSY'06

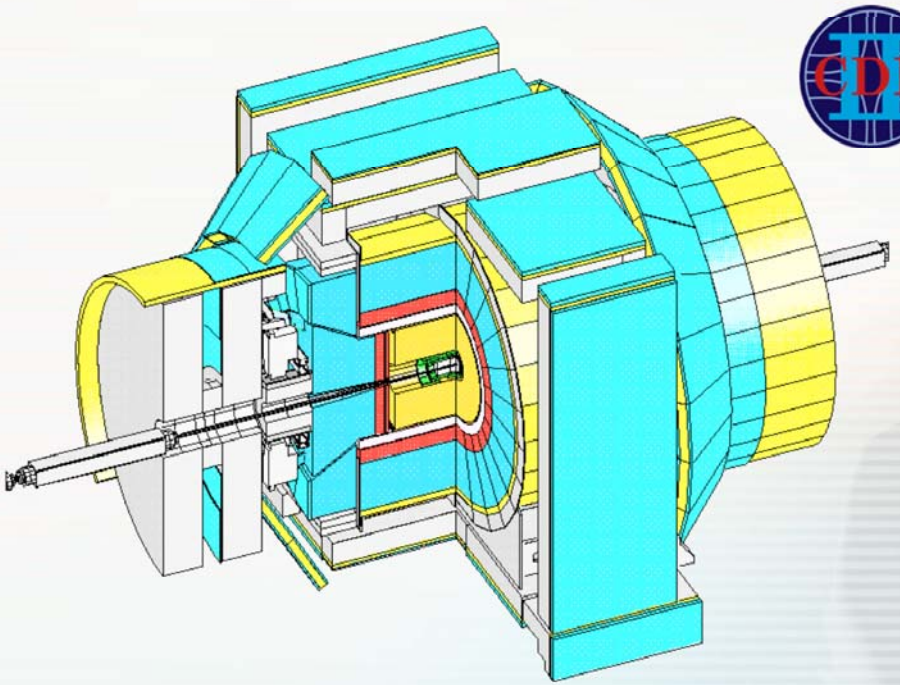
UC Irvine

June 16, 2006

The Tevatron Collider and Detectors



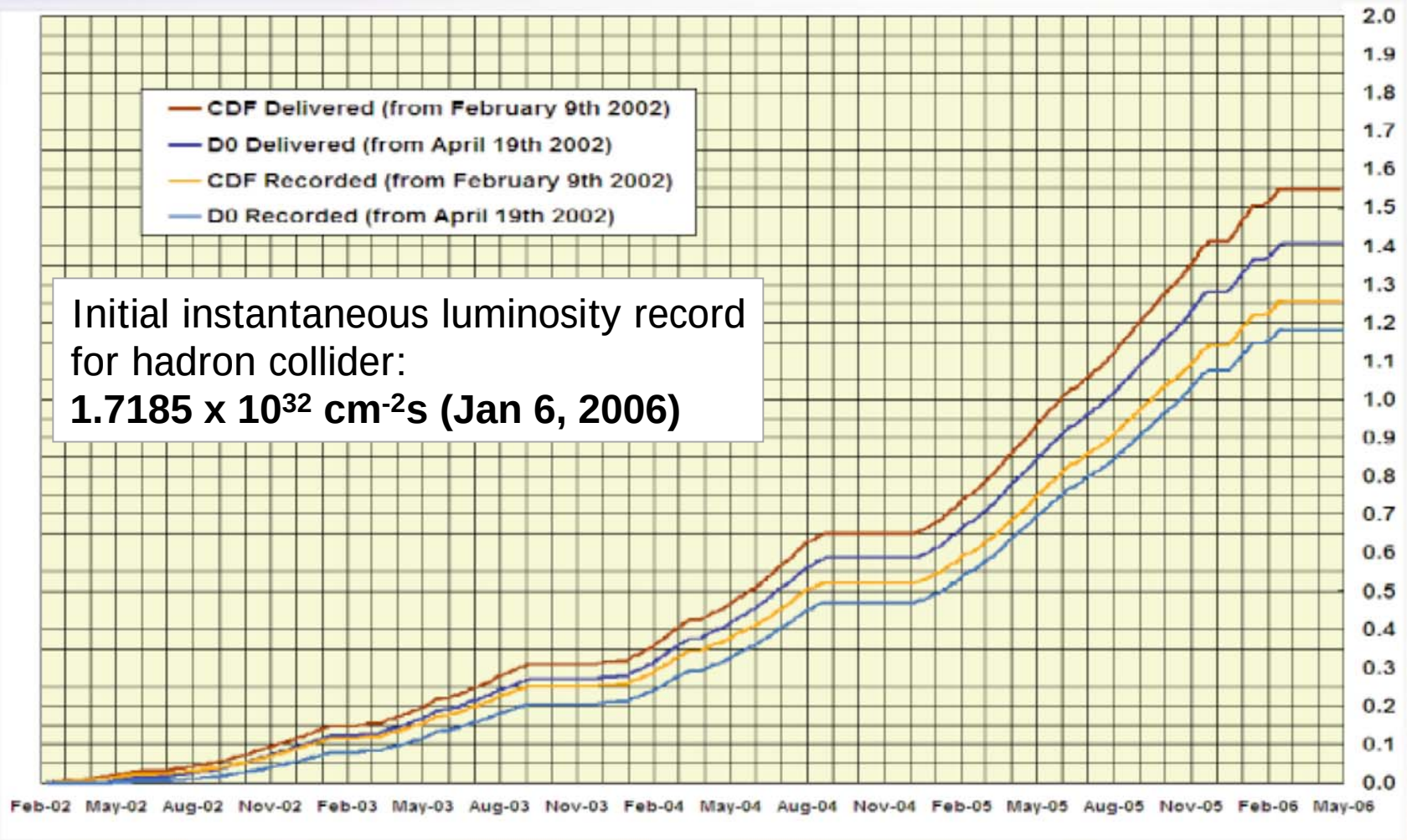




CDF and D0:

- General purpose detectors, axial and forward-backward symmetric
- Precision tracking (incl silicon detectors)
- Hadronic and EM calorimeters
- Muon detectors

Collected Data Samples

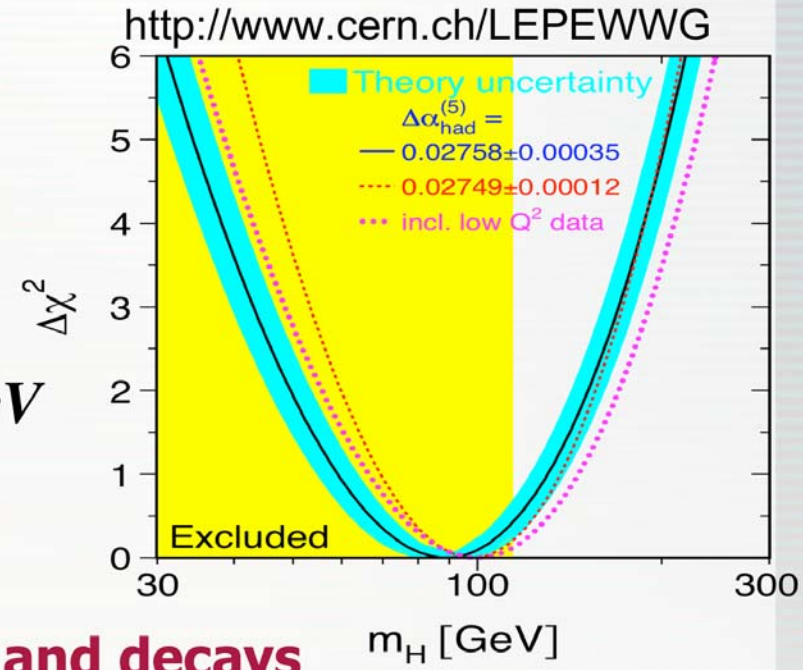


- ✓ **About 1.2 fb^{-1}/exp available for Summer'06 analyses**
- ✓ **Data taking is about to resume after a shutdown:**
  - **D0 silicon detector and trigger upgrades**

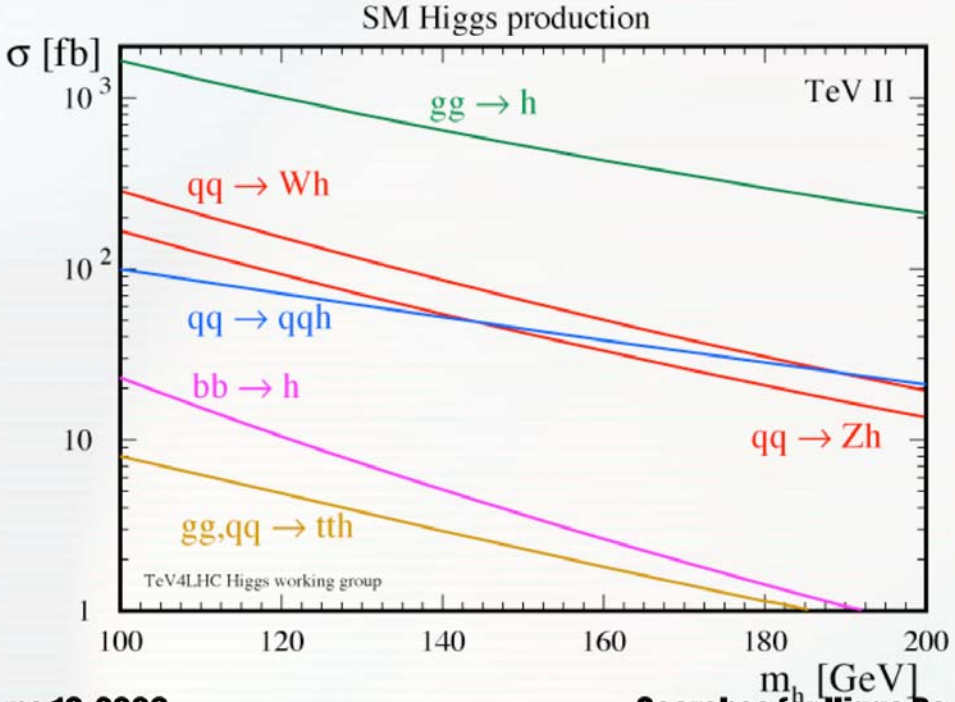
The SM Higgs

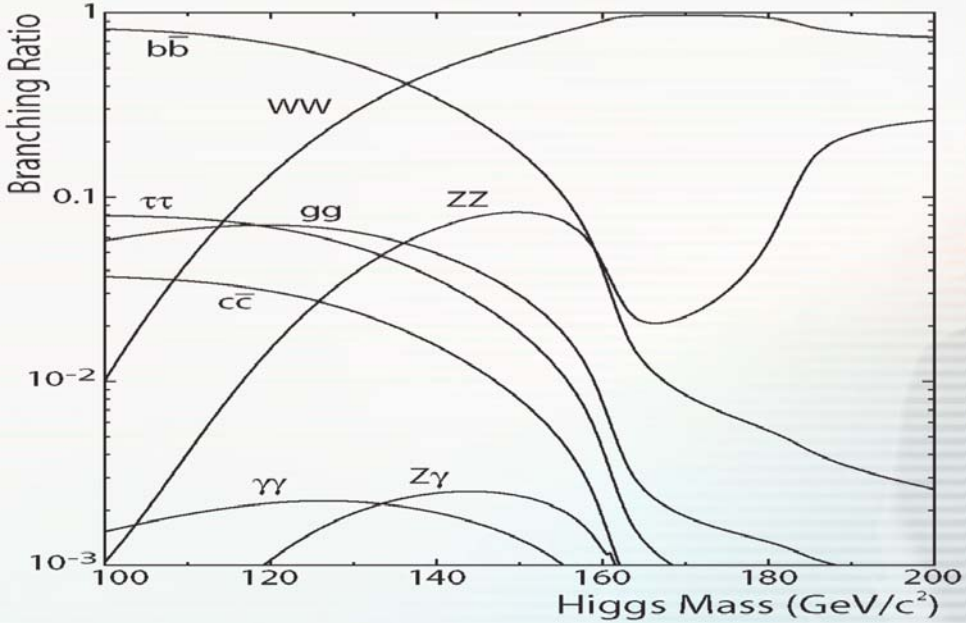
- Higgs mass is a free parameter
- LEP direct search: $m_H > 114.4\ GeV$
- Constraints from fits of EW data:
  - Best fit: $m_H = 89^{+42}_{-30} GeV$
  - 95% CL upper limit: $m_H < 175\ GeV$
- EW fit + direct search: $114.4 < m_H < 207\ GeV$

The EW fit suggests that SM Higgs is fairly light



Dominant production mechanisms and decays



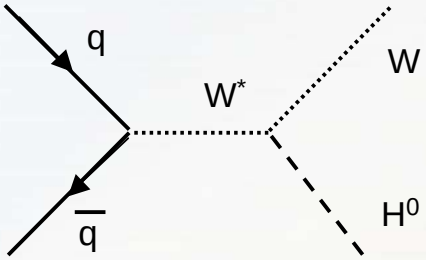


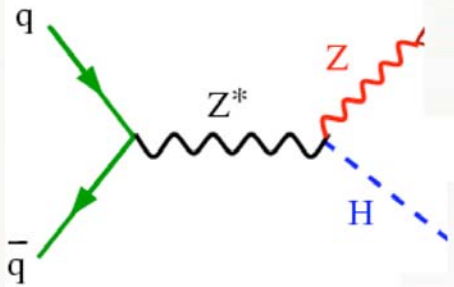
The "low-mass" region (m_H<135 GeV)

Observation of SM(-like) Higgs in this region will be consistent with MSSM

Best sensitivity:

- Production: H+Z/W, Z/W decay leptonically (suppress bg's)





- Higgs decay mode: H→bb (largest BR in the region)

- **Look for signal in the di-jet mass distributions**

Need good lepton identification, b-jet tagging, and jet energy resolution

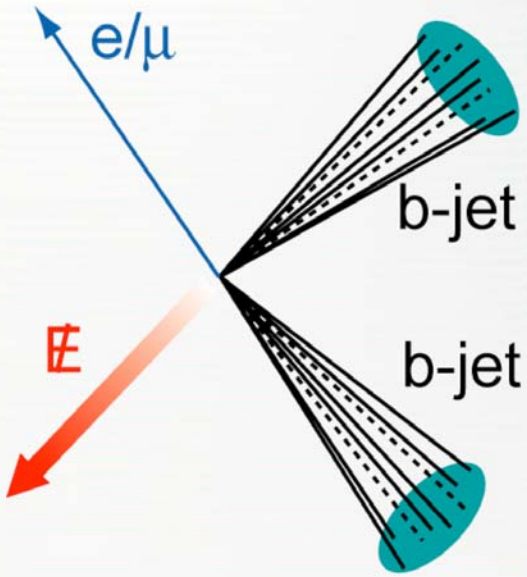
$WH \rightarrow l\nu b\bar{b}$

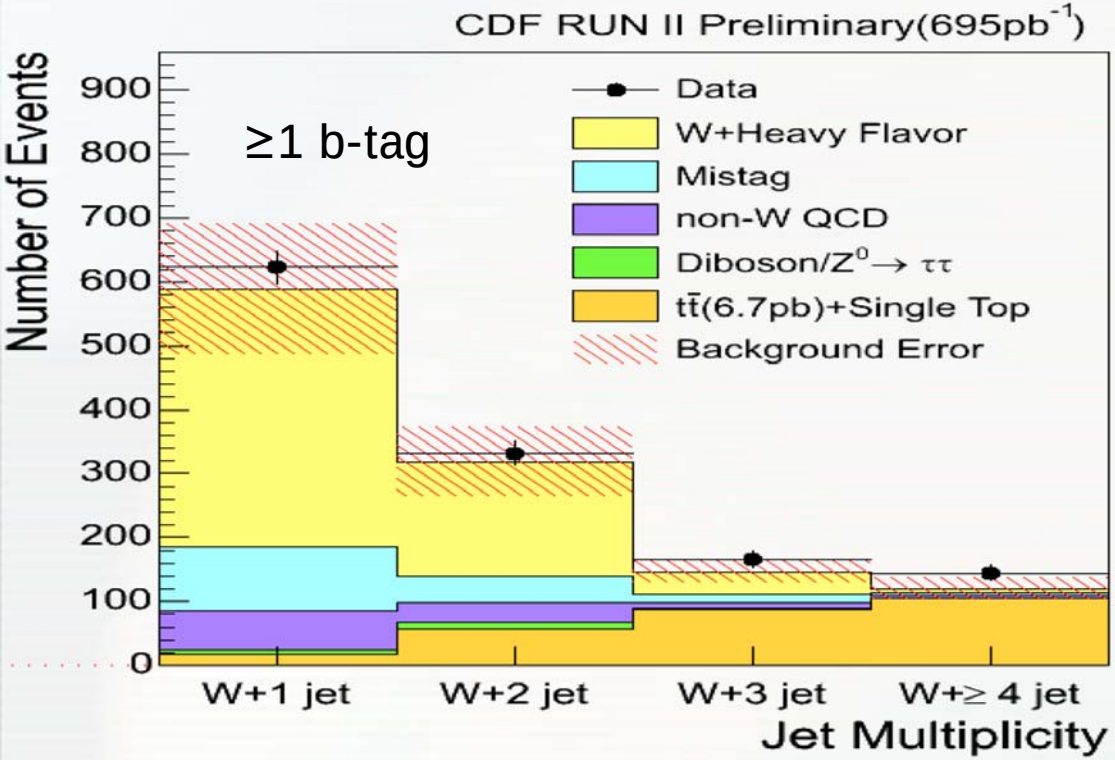
Detector signature

- ✓ Two b-jets
- ✓ One lepton (e or μ at present)
- ✓ Missing transverse energy

Dominant backgrounds

- W backgrounds: Wbb; Wcc, Wqq (false b-tag)
- Top backgrounds: Single top, tt
- Multi-jet



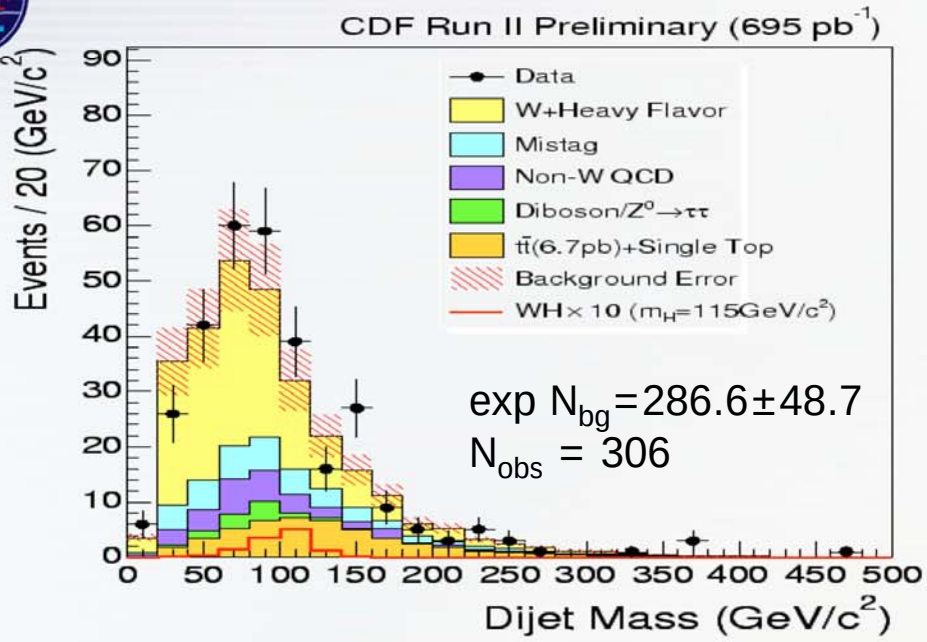


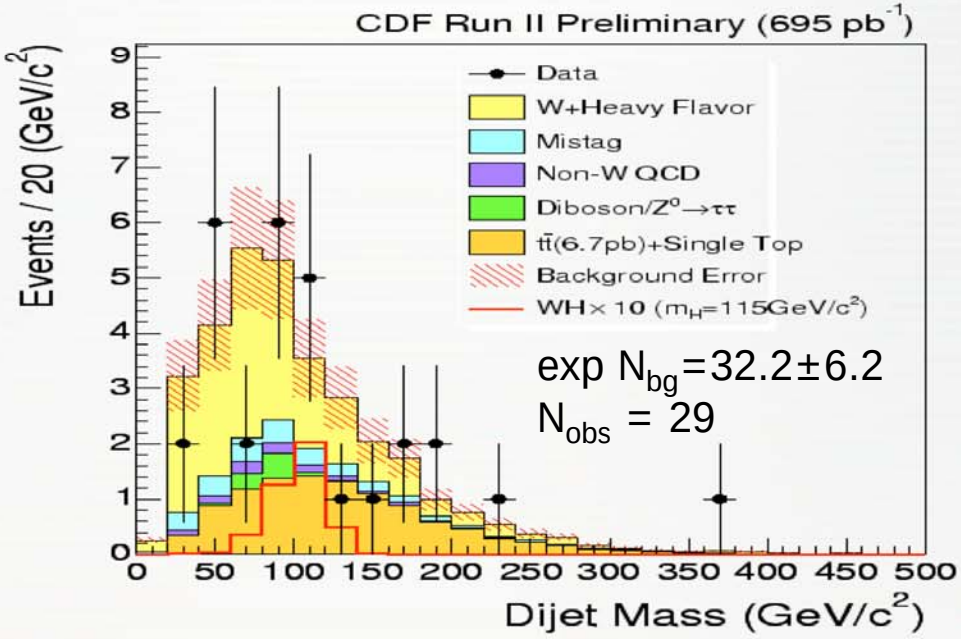
Event selection

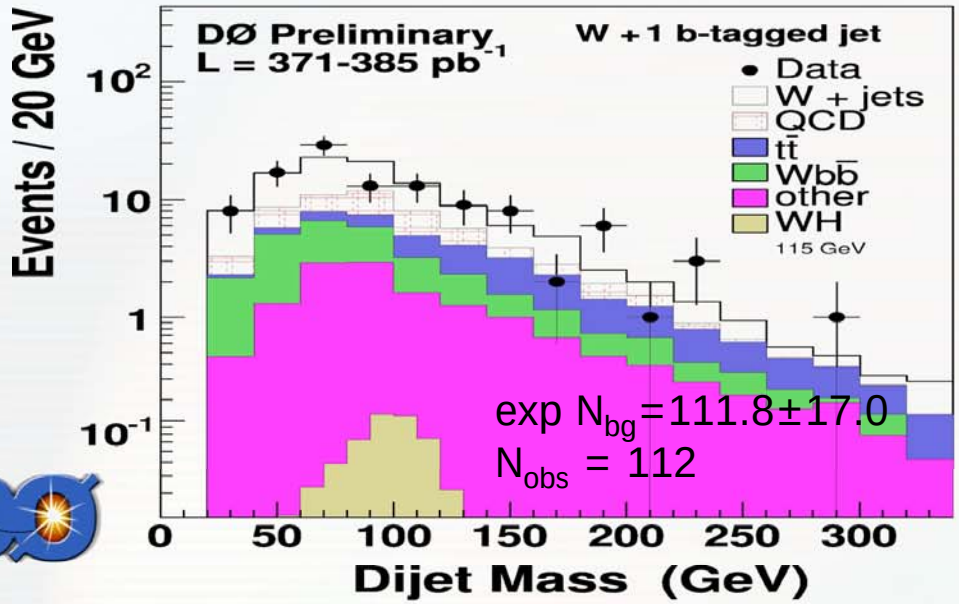
- ✓ Identified e/μ, p_T>20 GeV
- ✓ Two jets: E_T>15 GeV, |η|<2.0 (CDF);
  E_T>20 GeV, |η|<2.5 (D0);
- ✓ At least one of the jets b-tagged
- ✓ $\not\!\!E_T$>20 GeV (CDF); $\not\!\!E_T$>25 GeV (D0);
- ✓ Veto extra jets, Z→ℓℓ

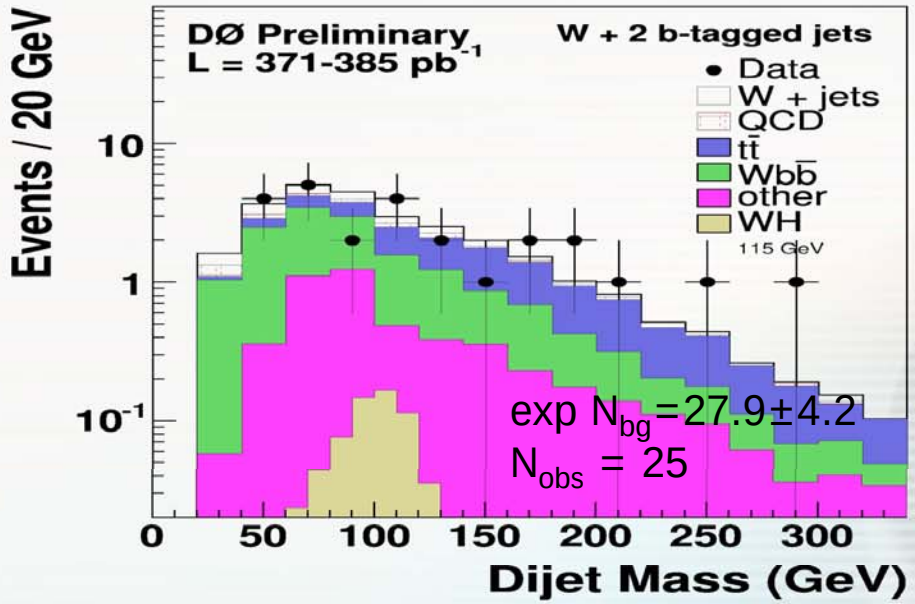
Look for signal in the di-jet mass distribution

$WH \rightarrow l\nu b\bar{b}$: Di-jet mass

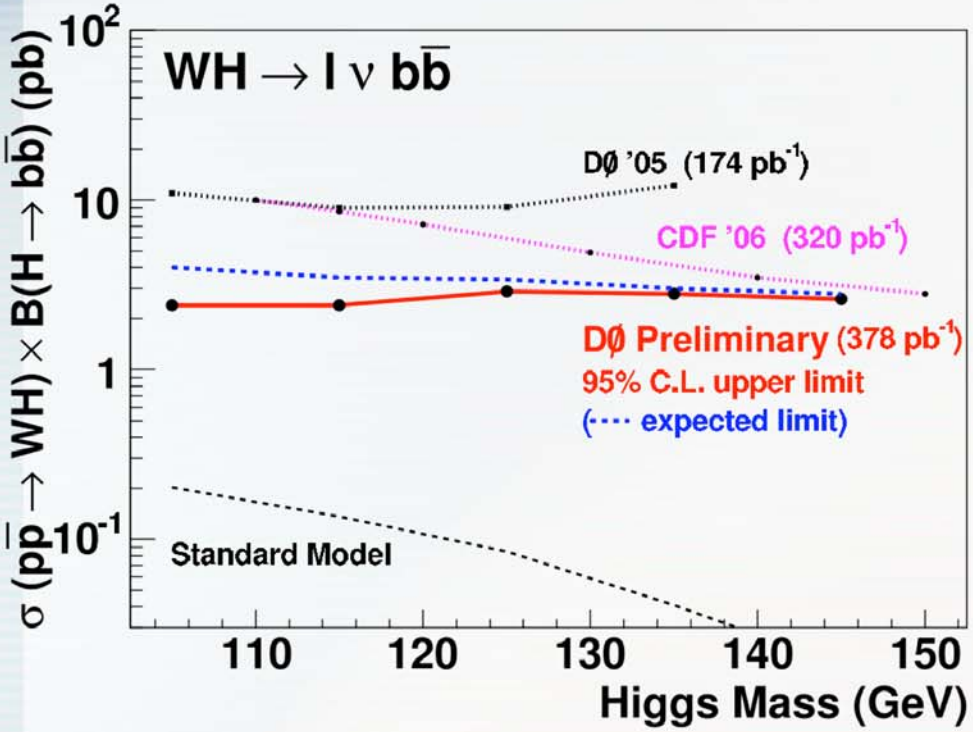


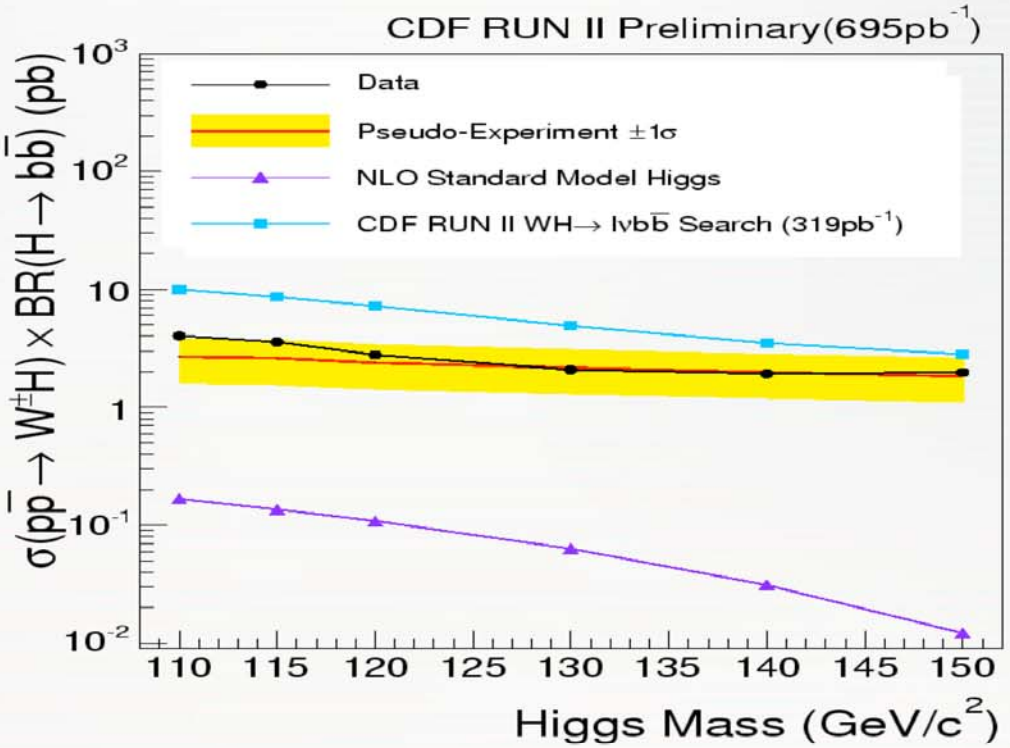






SM Higgs Limits from $WH \rightarrow l\nu b\bar{b}$

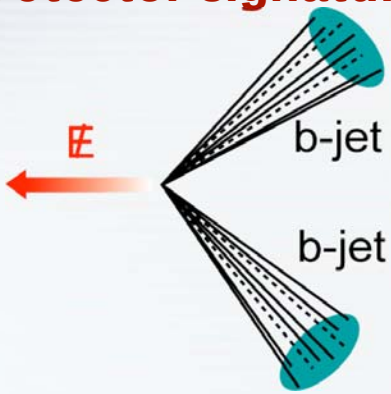




- **CDF is adding the remaining data, non-central leptons**
- **D0 is also updating to full sample**

$ZH \rightarrow \nu\nu b\bar{b}$

Detector signature



Event selection (CDF)

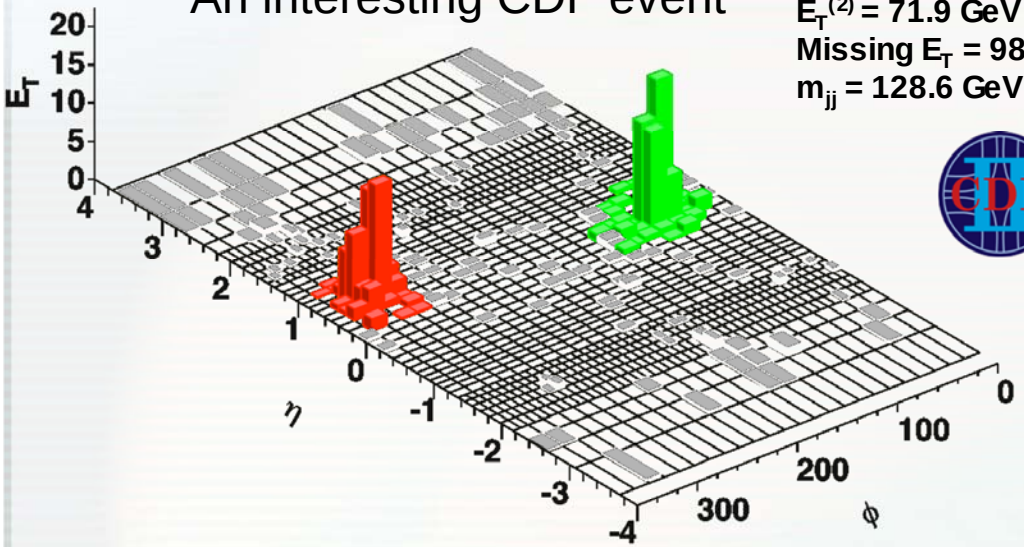
- Two jets, E_T>60,25 GeV
- At least on b-tag
- Lepton veto
- Veto extra jets with E_T>15 GeV
- Missing E_T>70 GeV, cut on direction
- Sliding di-jet mass cut for limit setting

Expected N_{bg}=19.7±3.5, N_{obs}=19

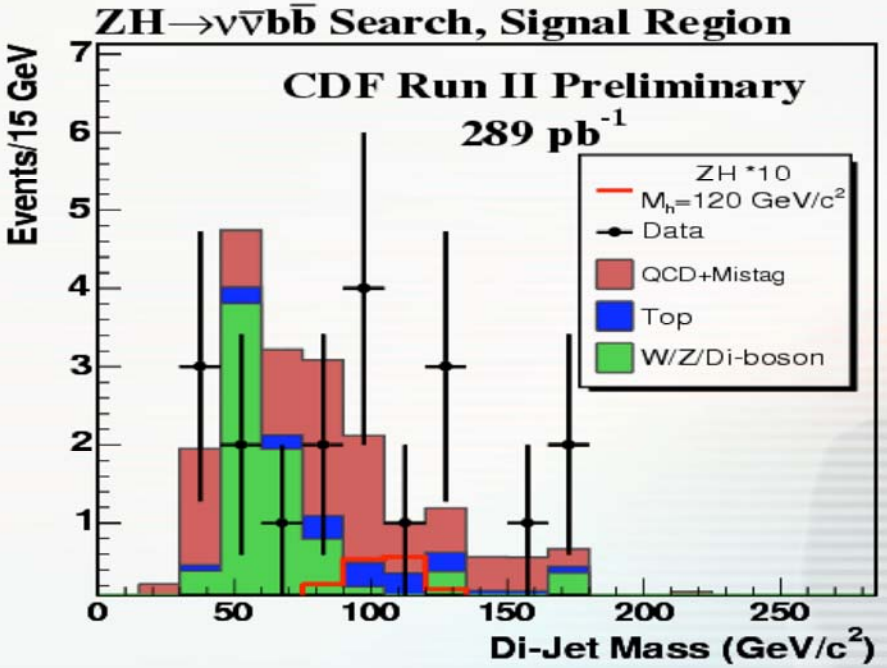
Dominant backgrounds:

- Multi-jet
- W/Z + heavy flavor
- Diboson: WZ (Z→bb)
- Top

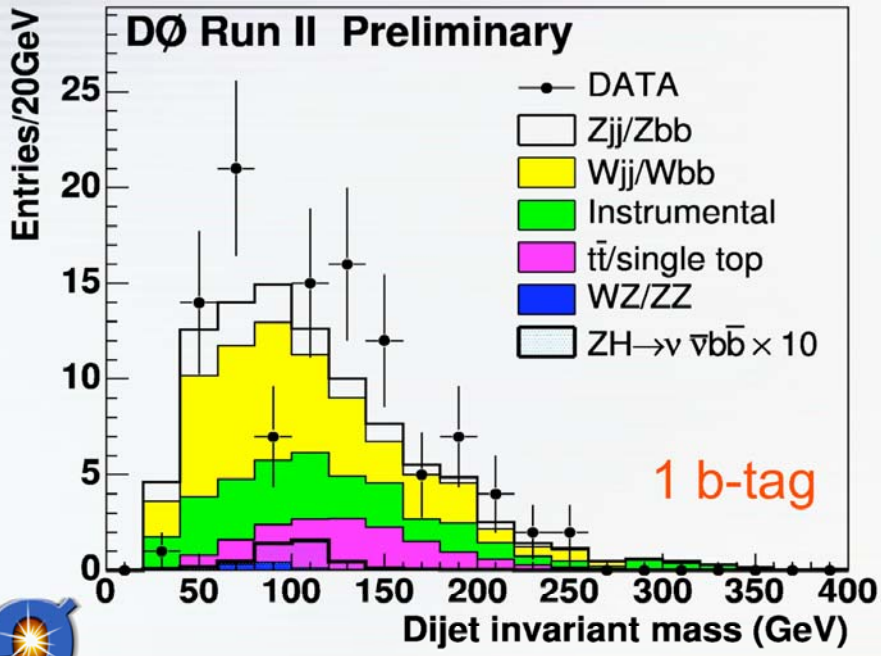
An interesting CDF event

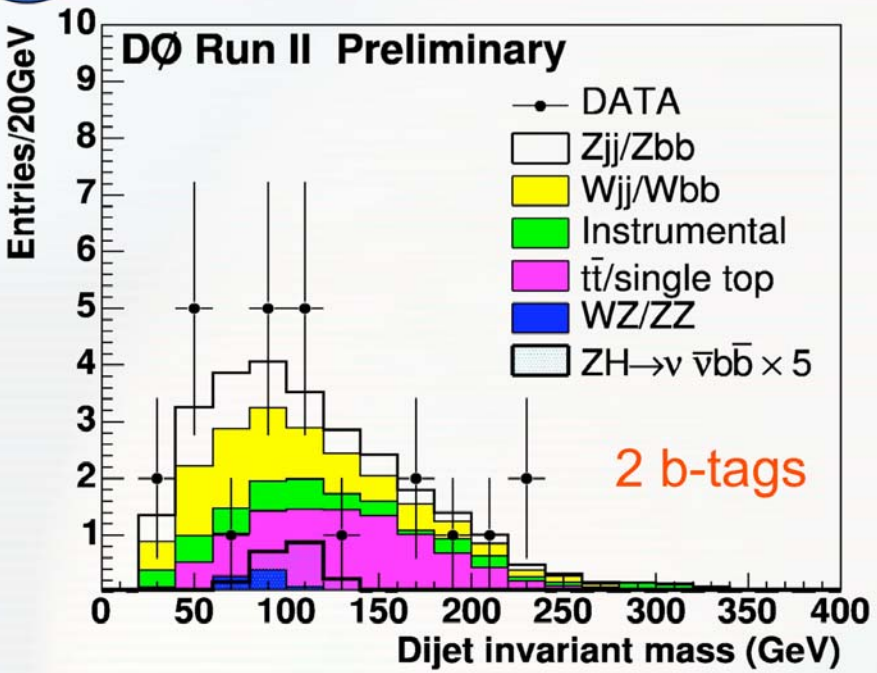


$E_T^{(1)}$ = 84.7 GeV
$E_T^{(2)}$ = 71.9 GeV (b-tag)
Missing E_T = 98.0 GeV
m_{jj} = 128.6 GeV



$ZH \rightarrow \nu\nu b\bar{b}$



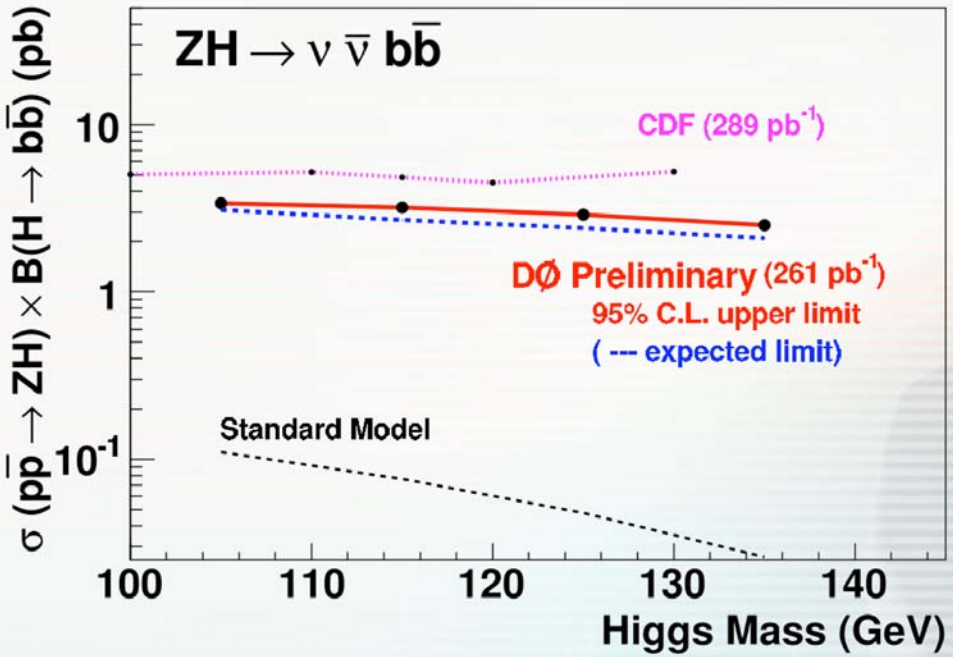


Event selection (D0)

- Two jets, E_T>20 GeV
- At least on b-tag, split samples into 1,2-tags
- Isolated track veto
- Missing E_T>50 GeV, cut on direction
- Additional cuts to suppress multijets
- Sliding di-jet mass cut

1 tag: expect N_{bg}=94.5, N_{obs}=106

2 tag: expect N_{bg}=27.0, N_{obs}=25

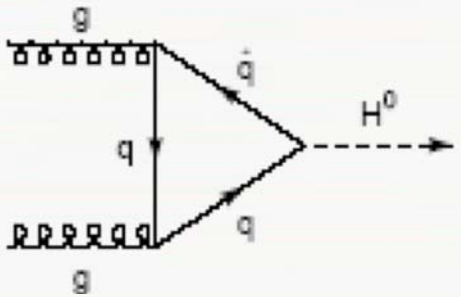


The "high-mass" region ($m_H > 150$ GeV)

Observation of SM Higgs in this region is bad news for MSSM

Best sensitivity:

- Production via gluon fusion (largest cross section)



- Decay: H→WW (largest BR in the region)
- Look at leptonic W decays (bg supression)

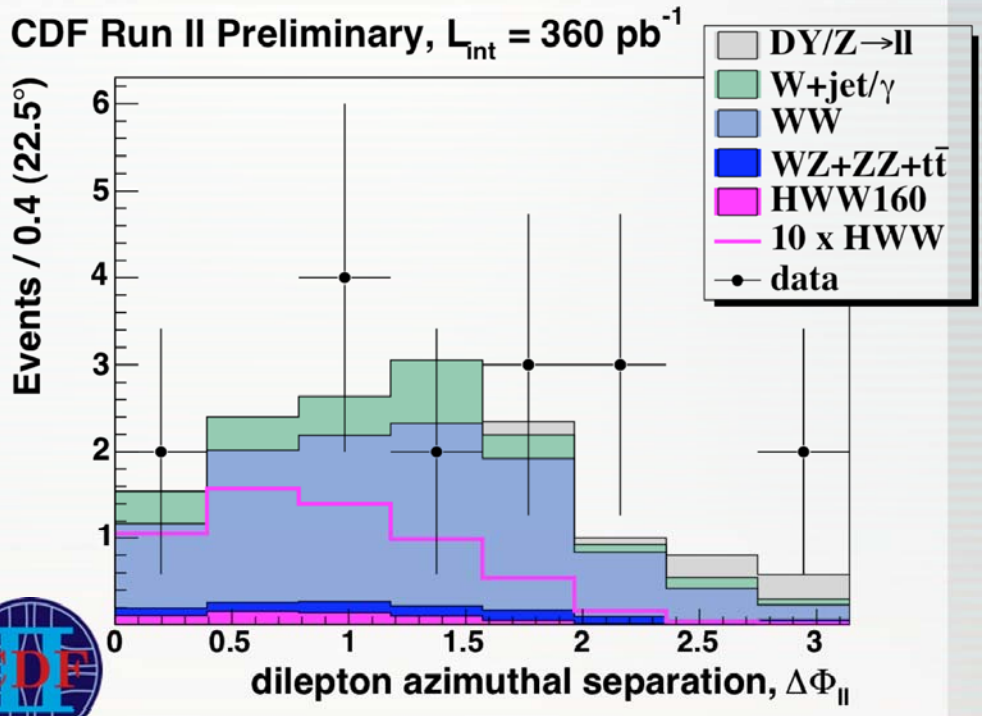
$H \rightarrow W^+W^- \rightarrow \ell\nu\ell\nu$

Detector signature:

- ✓ Two opposite-sign leptons
- ✓ Missing transverse energy in the event

Dominant backgrounds:

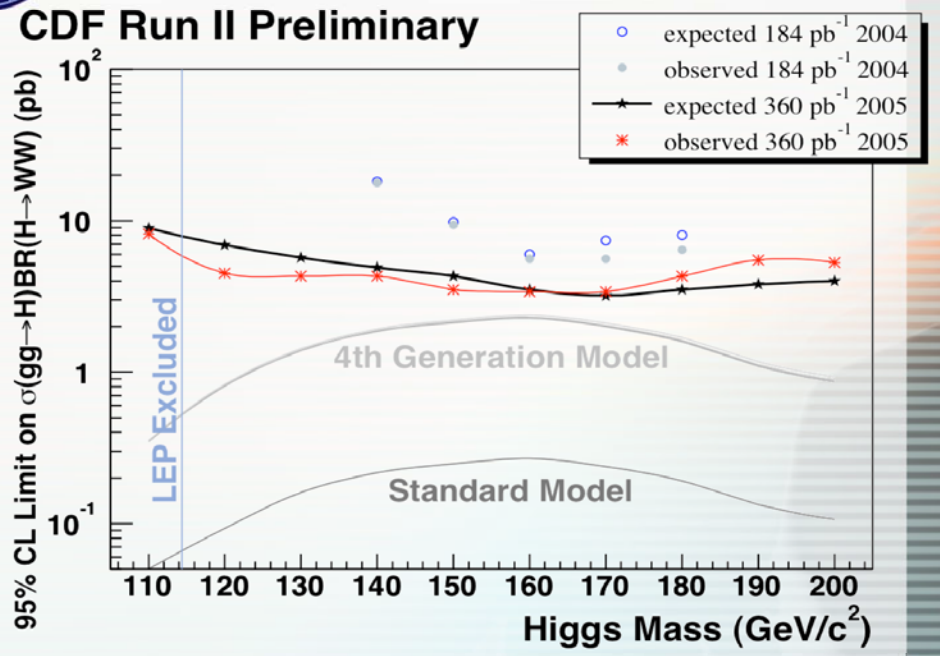
- ➢ Diboson: WW
- ➢ W+ jet(s)



Event Selection

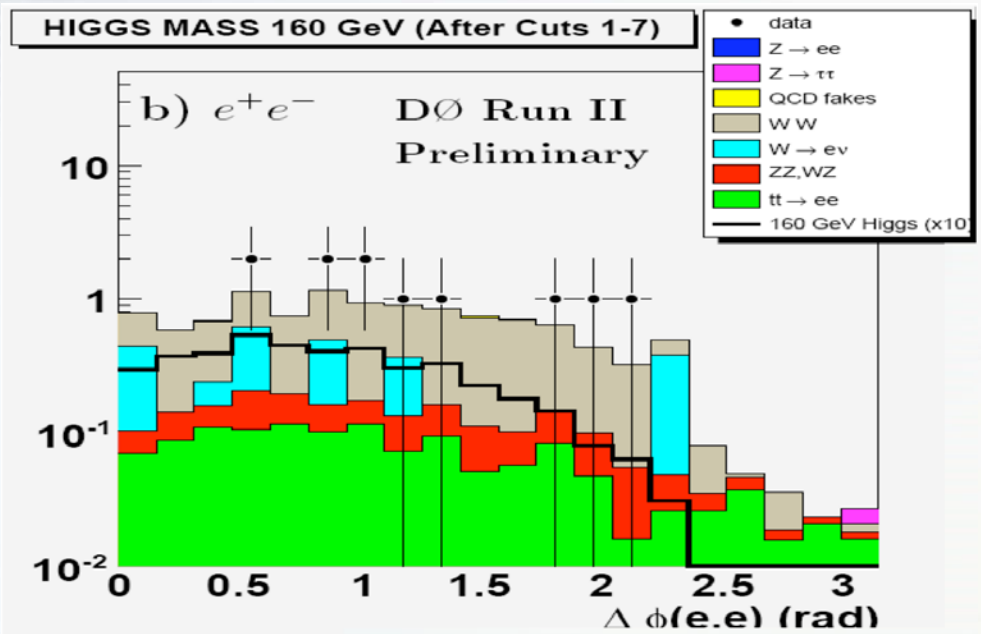
- **$p_T^{(1)}$ > 20 GeV (CDF); $p_T^{(1)}$ > 15 GeV (D0)**
- **$p_T^{(2)}$ > 10 GeV**
- **Higgs mass dependent event cuts:**
  - **relations between $p_T^{(1)}$, $p_T^{(2)}$, $\not\!\!E_T$**
  - **⇒ suppress Z/γ^*, WW**
- **Look in $\Delta\phi(l_1,l_2)$ distributions for signal**

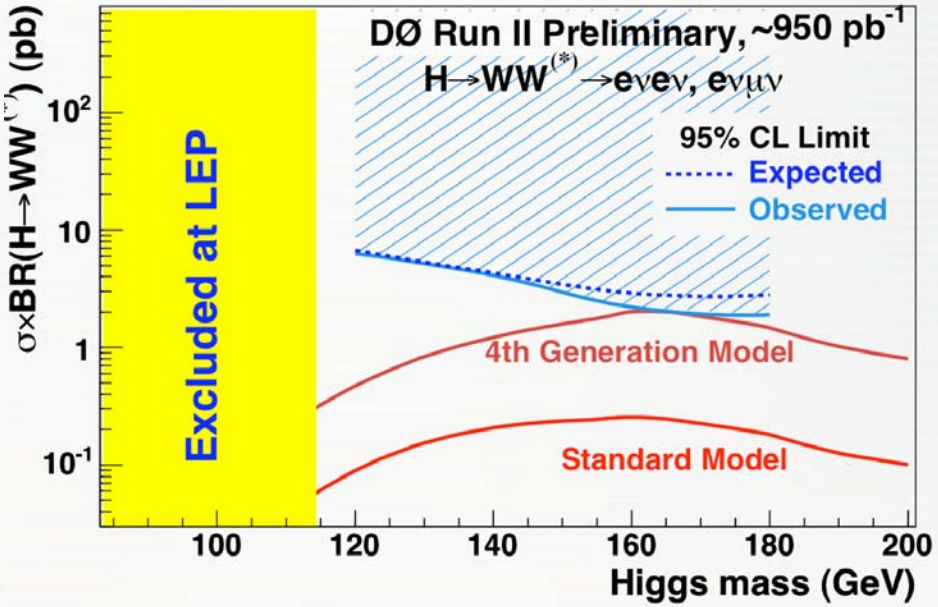
In the process of update with 1fb^{-1} of data and improved techniques

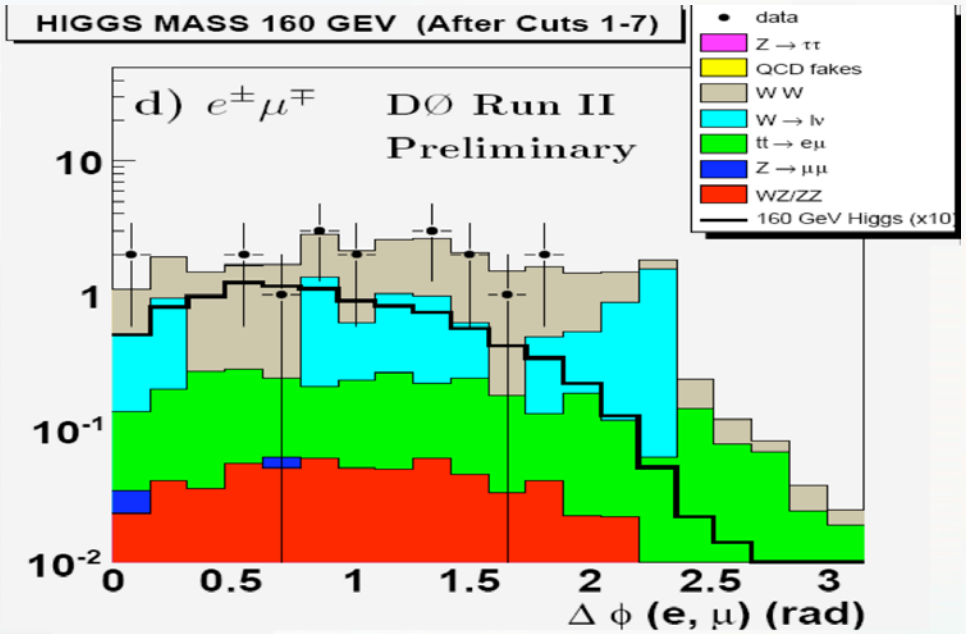


$H \rightarrow W^+W^- \rightarrow \ell\nu\ell\nu$

950 pb^{-1}!







Starting to exclude 4th Gen!

The μμ final state will be added soon ⇒ additional sensitivity

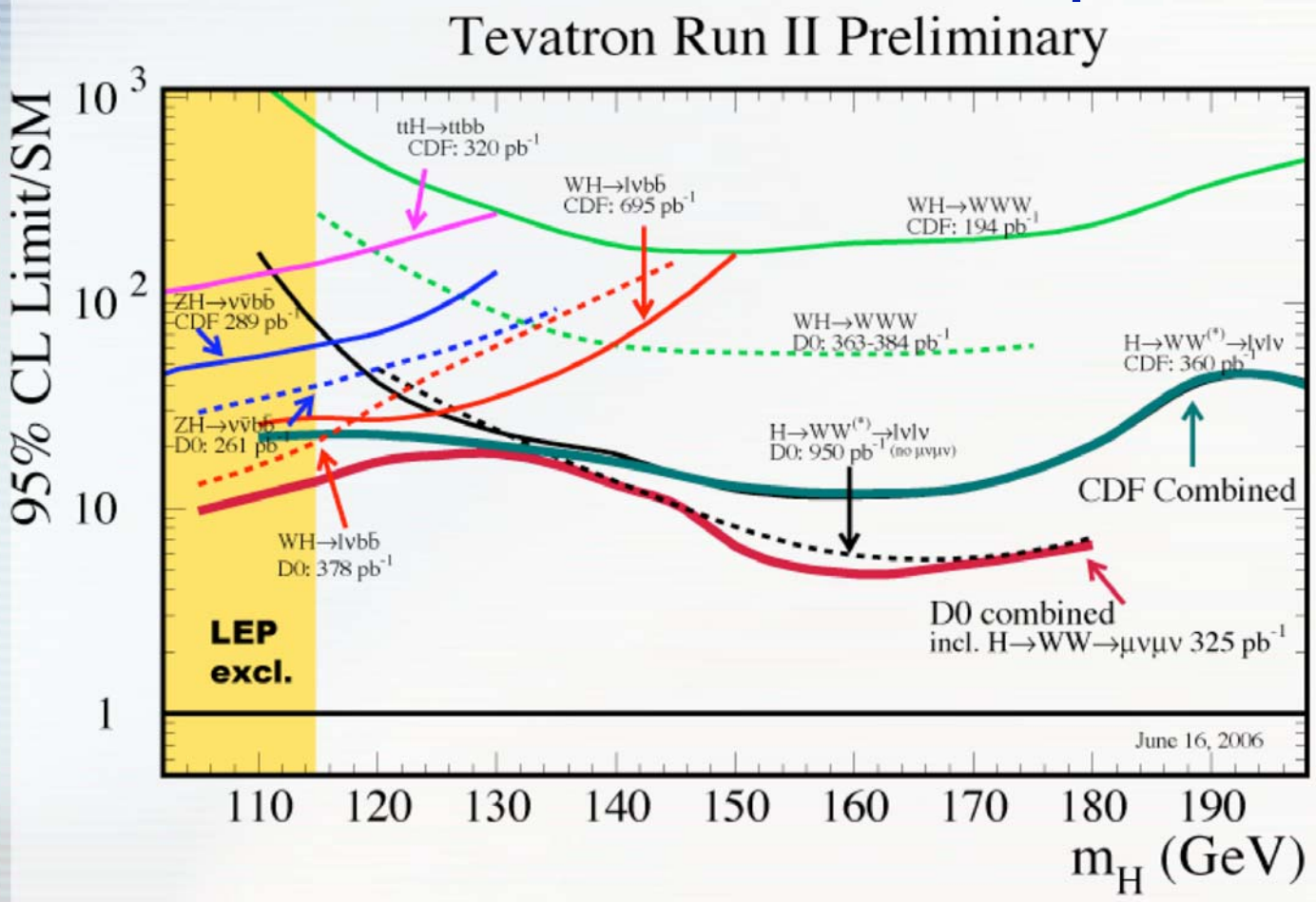
Other SM Higgs Searches

- **$WH \rightarrow WWW$ (CDF, D0)**
  - Detector signature - two like-sign leptons
  - Sensitive to high- and medium-mass Higgs
  - Somewhat overshadowed by the $gg \rightarrow H \rightarrow WW$ results, but still useful

- **$ttH \rightarrow WWbbbb$ (CDF)**
  - interesting for LHC
  - one lepton, ≥ 5 jets, ≥ 3 b-tags, Missing E_T
  - Expect $N_{bg} = 0.89 \pm 0.12$, observe 1 event

Summary of the SM Higgs Results

Ratio of observed limits to the SM expectation



	L_{int} (pb^{-1})	
Channel	**CDF**	**DØ**
WH→lνbb	695	378
ZH→ννbb	289	261
gg→H→WW	360	950
WH→WWW	194	363-384
ttH→ttbb	320	-

Included in the respective combinations

ZH→llbb in progress

Aiming to update all major channels with 1fb^{-1} this summer!

Need to combine to maximize sensitivity:

- Combine channels
- Combine CDF and D0 results

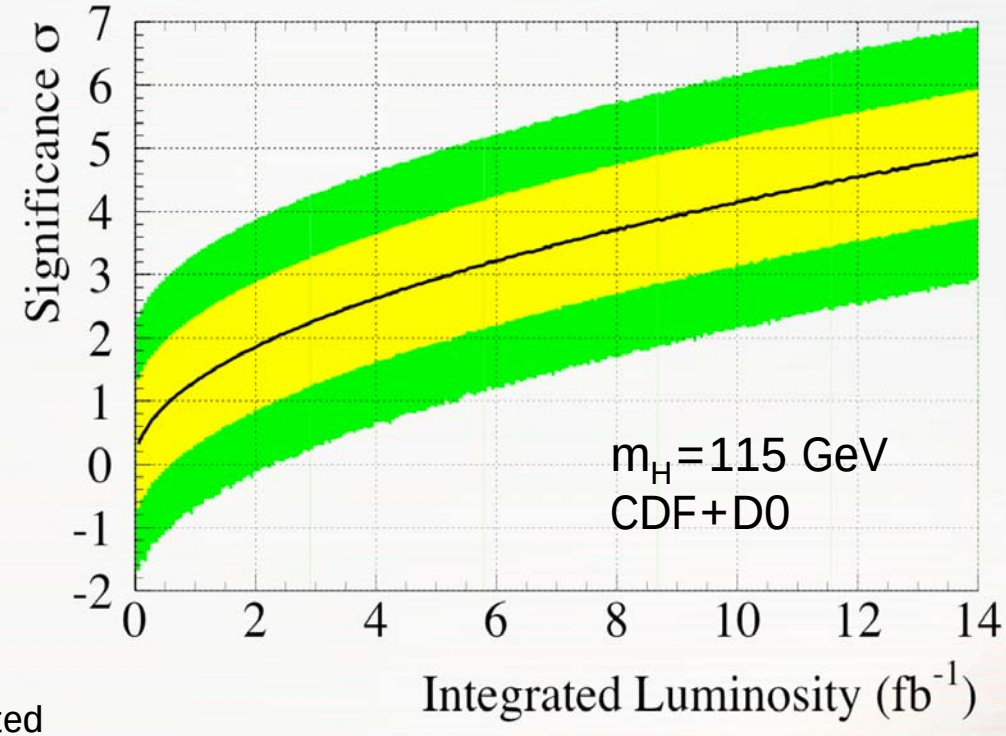
CDF/D0 combination group has been formed, working!

Improvements, Reach for SM Searches

- **In addition to combining, need to further improve each channel**
- **Many target areas, substantial overall effect**

	L_{int} Equivalent Factor $(s/\sqrt{b})^2$		
Improvement	WH→lνbb	ZH→ννbb	ZH→llbb
Mass resolution	1.7	1.7	1.7
Continuous b-tag (NN)	1.5	1.5	1.5
Forward b-tag	1.1	1.1	1.1
Forward leptons	1.3	1.0	1.6
Track-only leptons	1.4	1.0	1.6
NN Event Selection	1.75	1.75	1.0*
WH signal in ZH	1.0	2.7	1.0
Product of above	8.9	13.3	7.2
CDF+DØ combination	2.0	2.0	2.0
All combined	17.8	26.6	14.4

* already implemented



(based on the sensitivities from Autumn'05)

These 3 channels give CDF and D0 sensitivity to m_H<135 (projected luminosities)

The reach in the higher-mass region by H→WW is very promising!

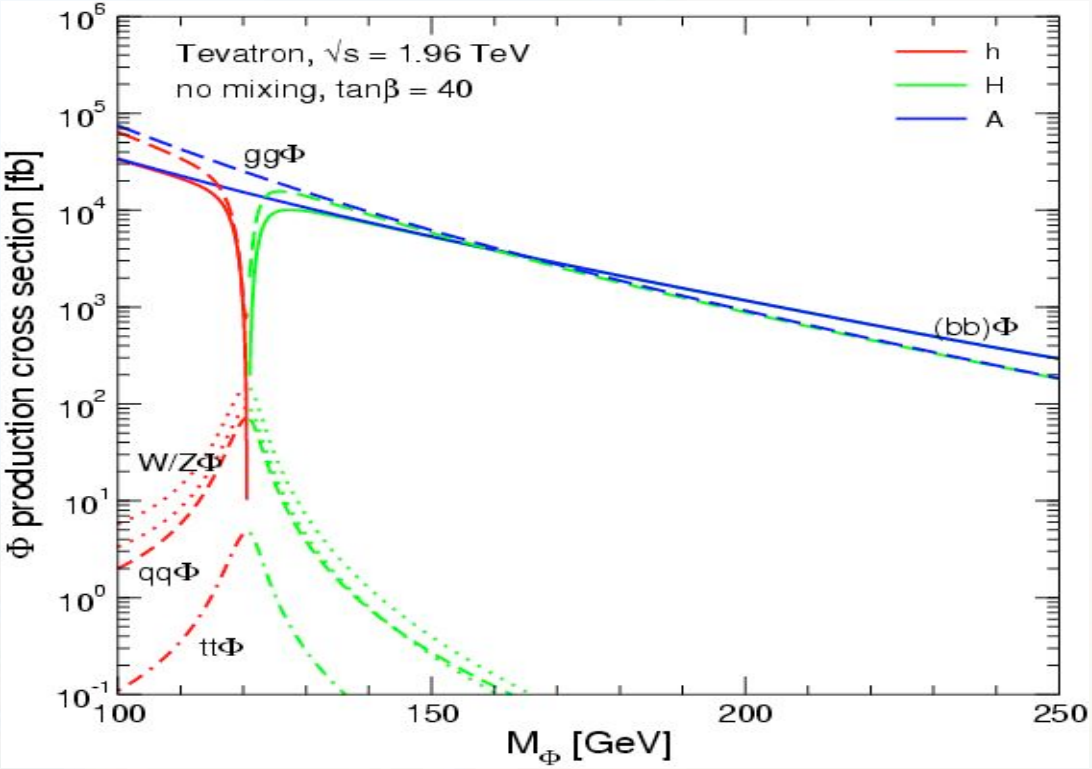
The MSSM Higgs Sector

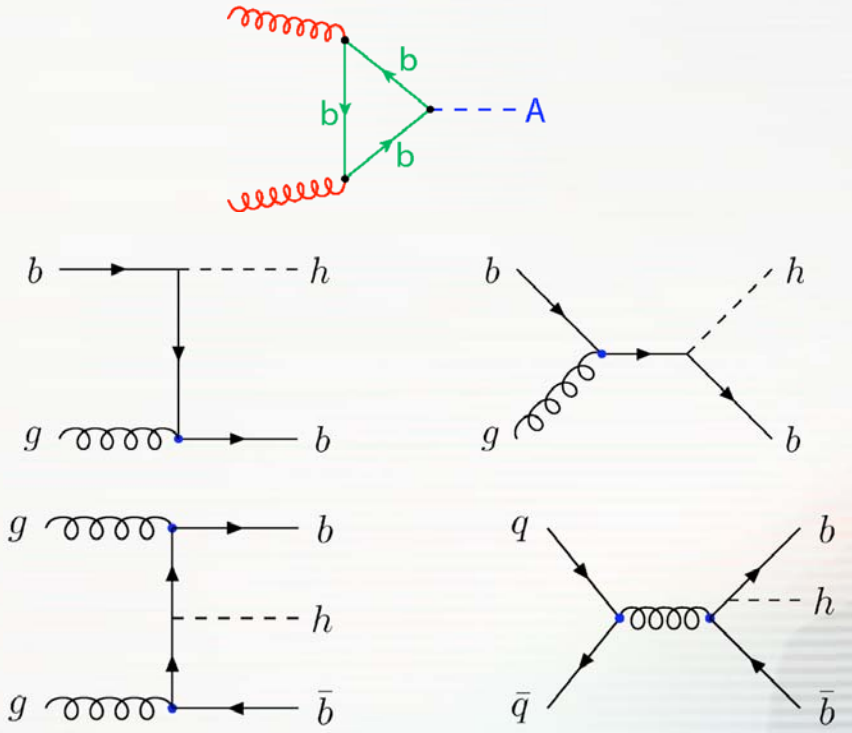
MSSM ⇨ minimal Higgs content, 2HDM

$H^{\pm}$; A (CP-odd); h, H (CP-even)

In the following ϕ is used to denote any of A,h,H

- **Tree-level parameters: $\tan\beta = v_u/v_d$, m_A**
- **Yukawa couplings of A to b, τ ~tanβ (but modified by radiative corrections)**
- **For large tanβ one of the h/H is SM-like, the other almost mass-degenerate with A, similar couplings**
- **The mass of the SM-like Higgs is <130 GeV (consistent with the EW fit!)**





Dominant A decays: bb (~85-95%) and ττ (~5-15%)

MSSM Higgs Searches

- Charged Higgs
- Neutral Higgs with tanβ-enhanced couplings

Interpret the results in the m_h^{max} and no-mixing scenarios

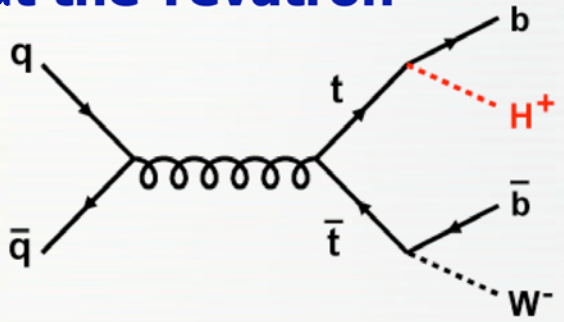
Carena, Heinemeyer, Wagner, and Weiglein, hep-ph/0202167

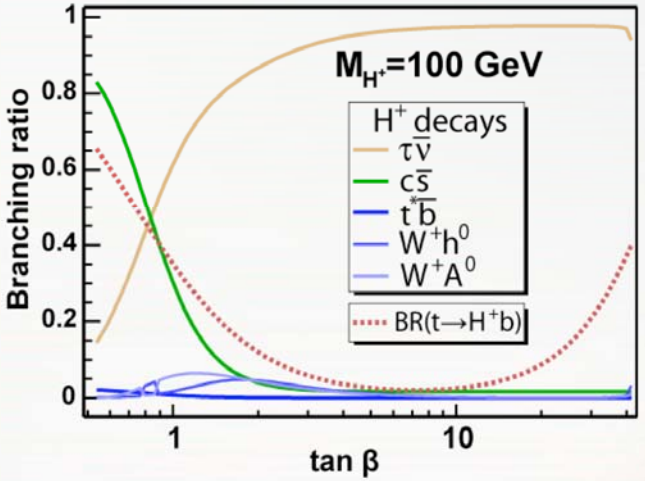
Search for Charged MSSM Higgs

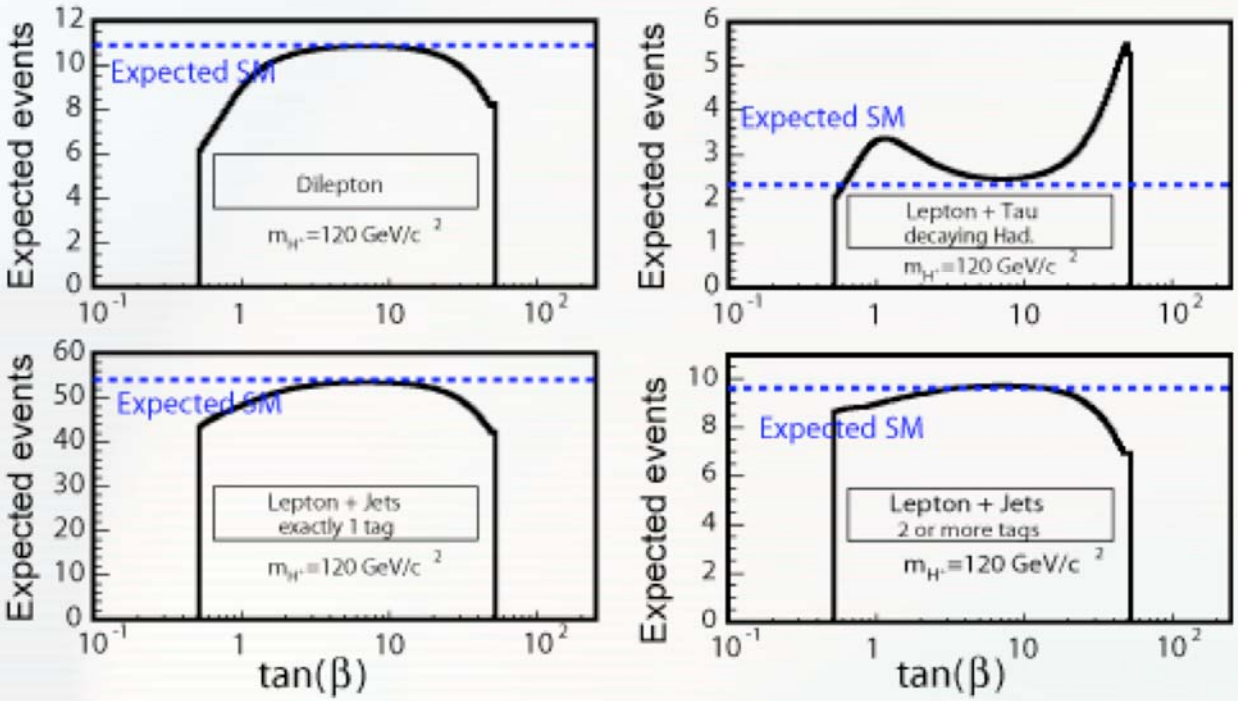
CDF Collaboration, PRL 96, 011802 (2006)

$H^{\pm}$ from $t \to bH^{+}$ is the most accessible mechanism at the Tevatron

- **$H^{\pm}$ modifies top BR's (mostly at large and small tanβ)**
- **$W^{\pm}$ and $H^{\pm}$ decay modes differ: take advantage of different topologies in tt final states**
- **Constraint: can probe only $m_H < m_t - m_b$**







Expected number of events in the SM and MSSM for four topological final states

(L_{int} = 192 pb^{-1})

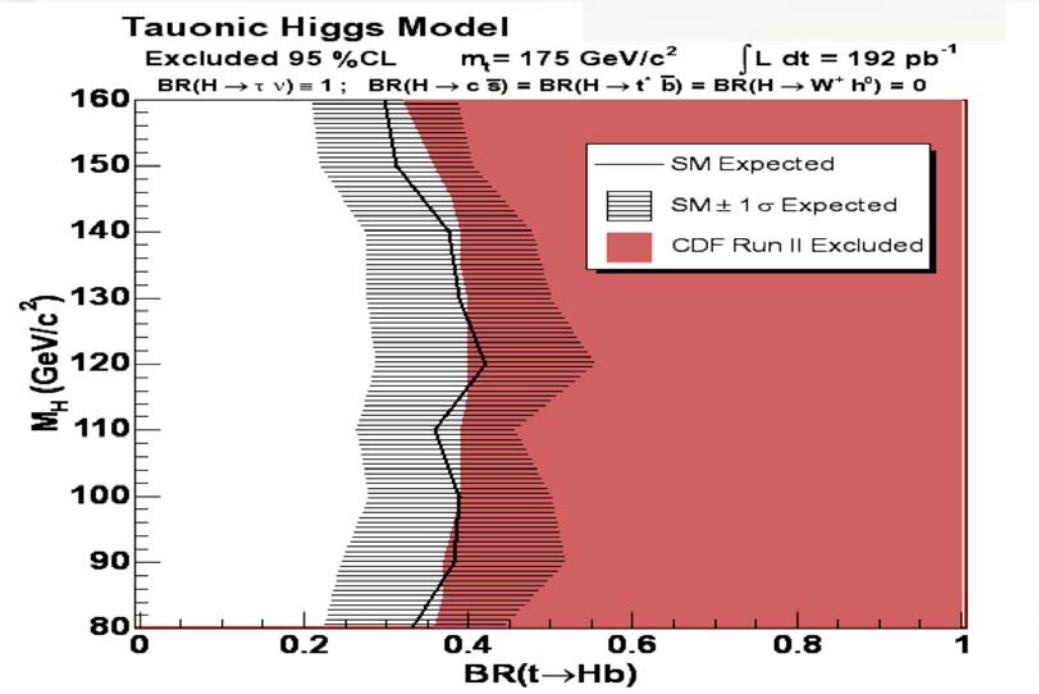
Search for $H^{\pm}$

Final state	bg events	SM exp	data
2ℓ + jets	2.7±0.7	11	13
ℓ+ jets (1b)	20.3±2.5	54	49
ℓ + jets (≥2b)	0.94±0.17	10	8
$\ell + \tau_h$ + jets	1.3±0.2	2	2

Consistent with the SM

The results can be interpreted in different MSSM scenarios.

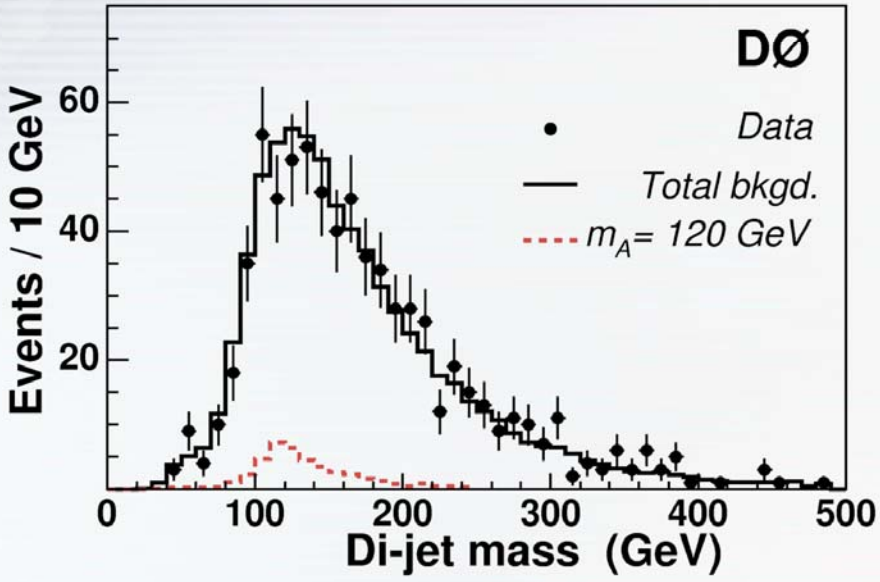
Here we show the "tauonic model": BR($H^+ \to \tau\nu$) = 1



- **This search will improve significantly with higher statistics**
- **Move from counting to including kinematic distributions**

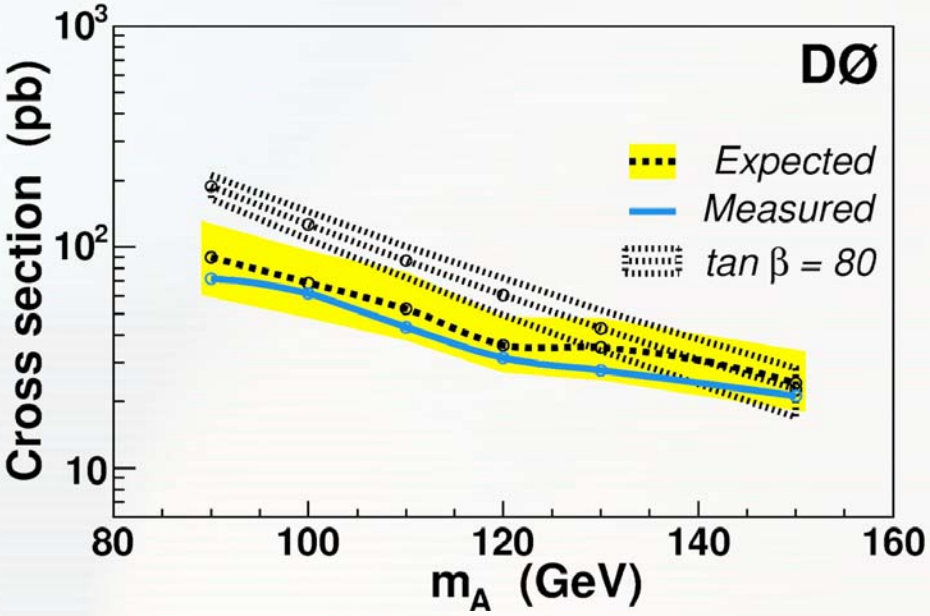
MSSM Higgs: $b(\bar{b})\phi \rightarrow b(\bar{b})b\bar{b}$

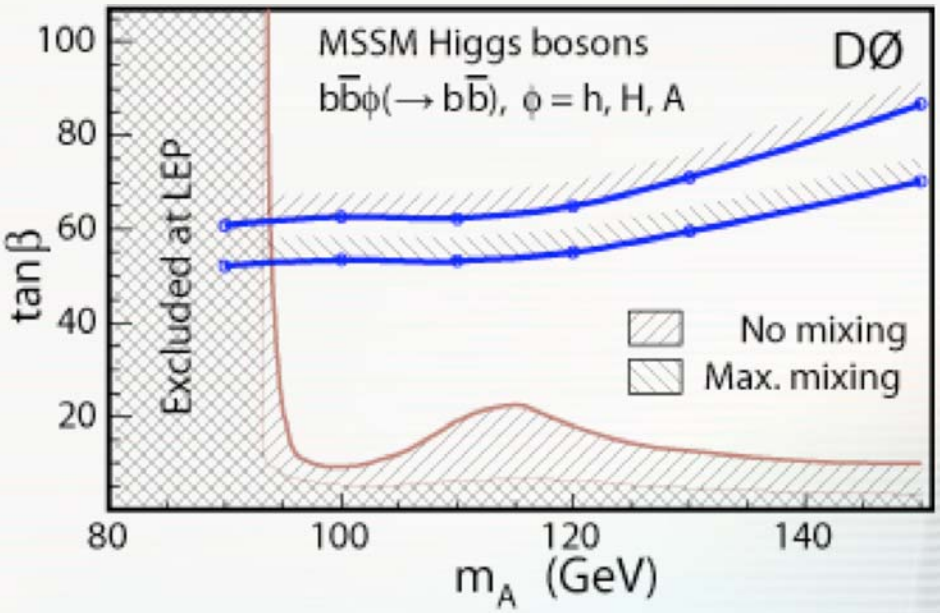
D0 Collaboration, PRL 95, 151801 (2005)



- Select events with at least 3 b-tagged jets
- Use double-tagged sample for bg shape
- Signal extraction from the di-jet mass distribution (2 highest-E_T jets)
- Signal acceptance: 0.3-1.0% (m_A=90-150 GeV)

L_{int} = 260 pb^{-1}





CDF result with 1fb^{-1} and update from D0 are in preparation

MSSM Higgs→ττ

Mode	Fraction (%)	Comment
$\tau_e\tau_e$	3	large $Z/\gamma^*\to ee$ bg
$\tau_\mu\tau_\mu$	3	large $Z/\gamma^*\to\mu\mu$ bg
$\tau_e\tau_\mu$	6	low jet bg
$\tau_e\tau_{had}$	23	golden
$\tau_\mu\tau_{had}$	23	golden
$\tau_{had}\tau_{had}$	41	challenging (jet bg)

Advantages of the Higgs→ττ mode:

- ✓ Probes all production modes
- ✓ Weaker dependence of sensitivity on SUSY parameters/corrections (see Carena et al., hep-ph/0511023)

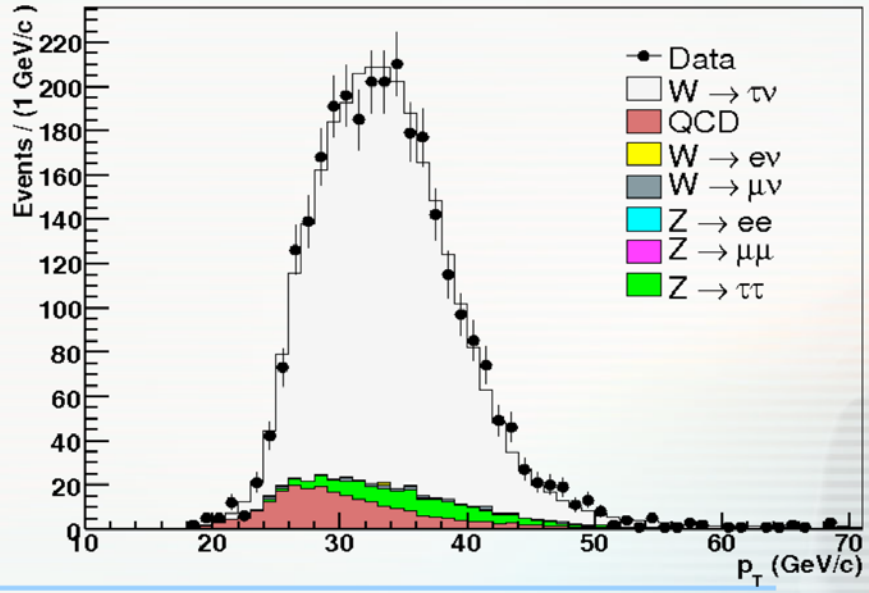
Challenge: idintification of τ_{had}

CDF: Two-cone algorithm, $p_{had}(\vec{p},E)$ from tracks and π^0's

D0: NN selection, $p_{had}(\vec{p},E)$ from calorimeter measurement

Higgs signal extraction (CDF and D0): from partial di-tau mass

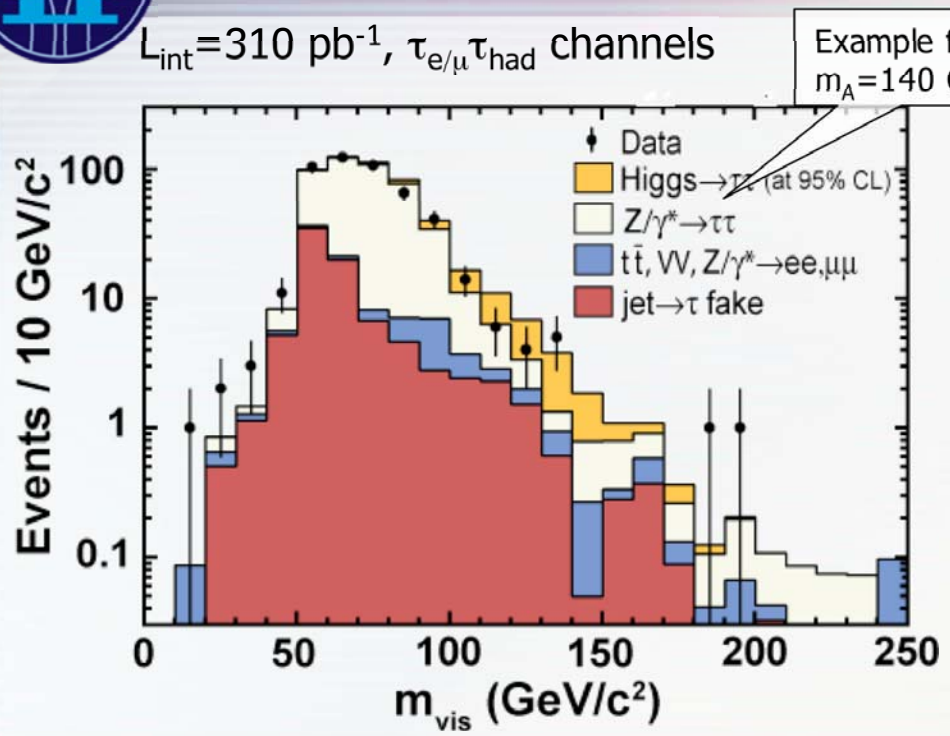
Example of reconstructed τ_{had} (CDF): spectrum of taus from a W→τν sample



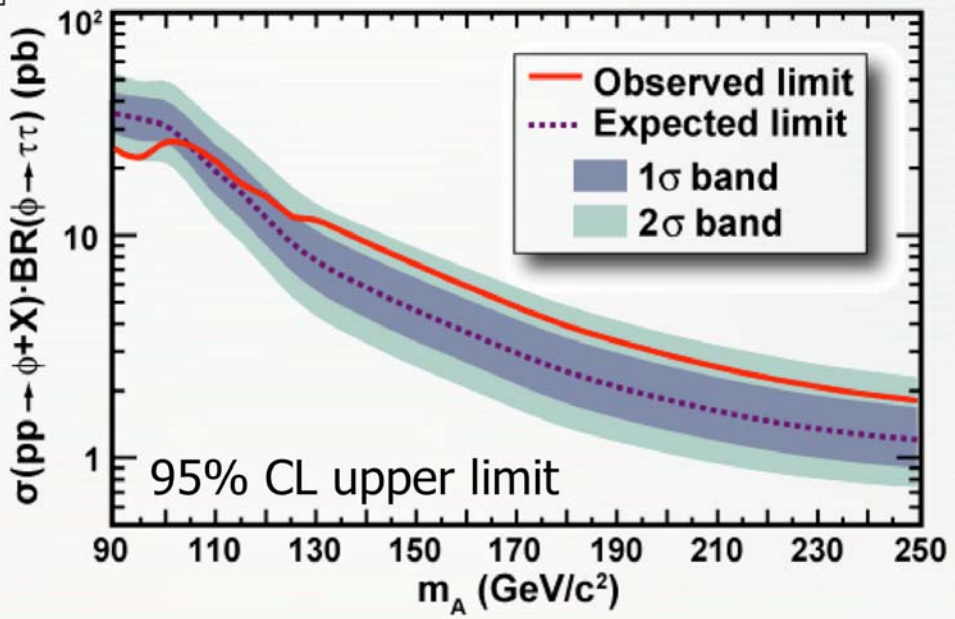
τ_e, τ_μ, τ_{had} are shorthand notations for $\tau\to e\nu\bar{\nu}$, $\tau\to\mu\nu\bar{\nu}$, and $\tau\to$*hadrons* ν, respectively.

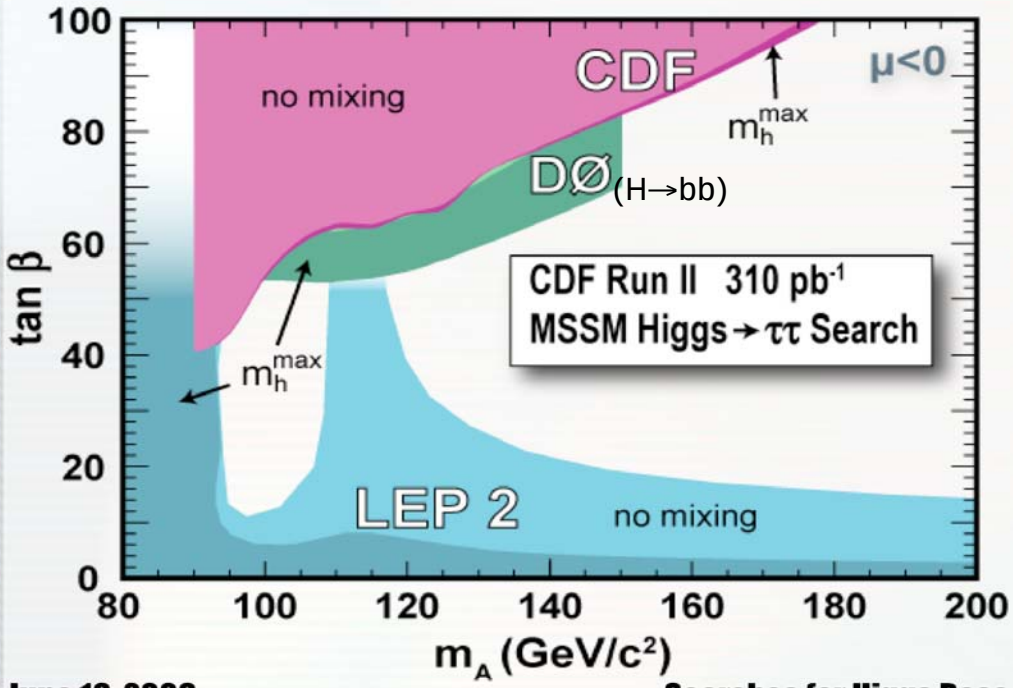
MSSM Higgs→ττ

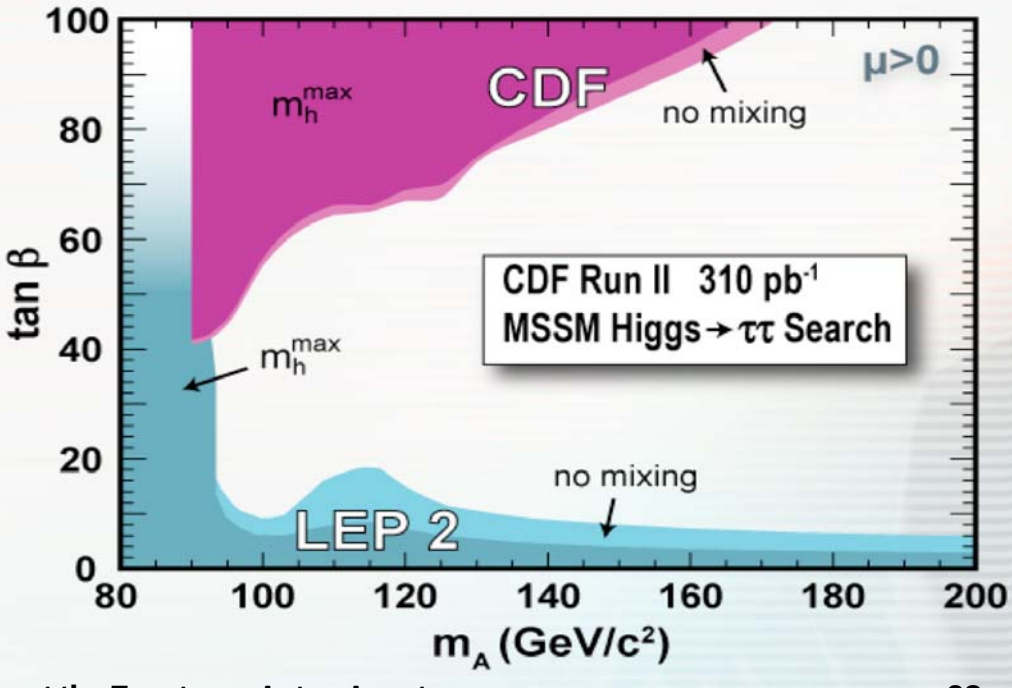
L_{int}=310 pb^{-1}, $\tau_{e/\mu}\tau_{had}$ channels



CDF Collaboration, PRL 96, 011802 (2006)



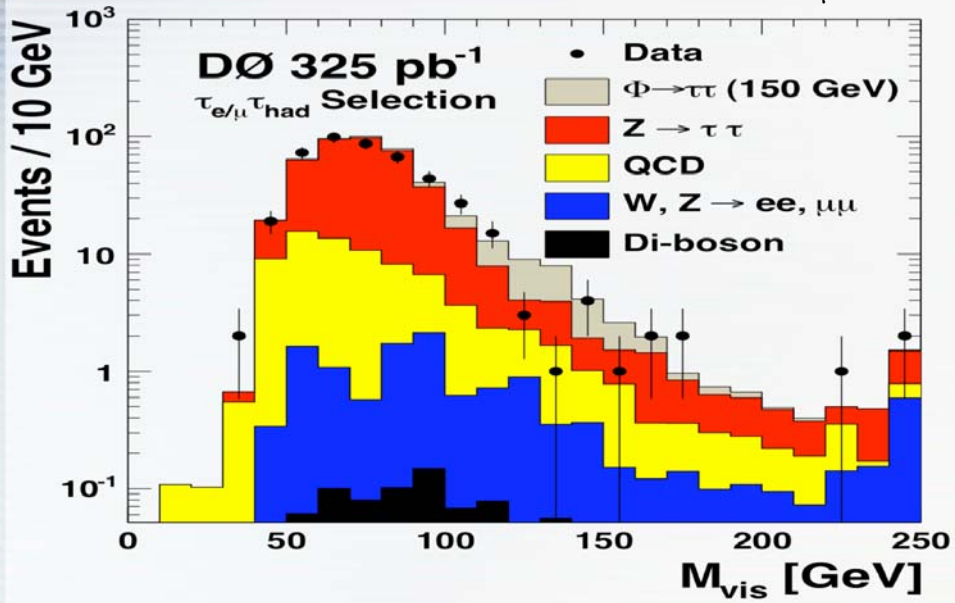


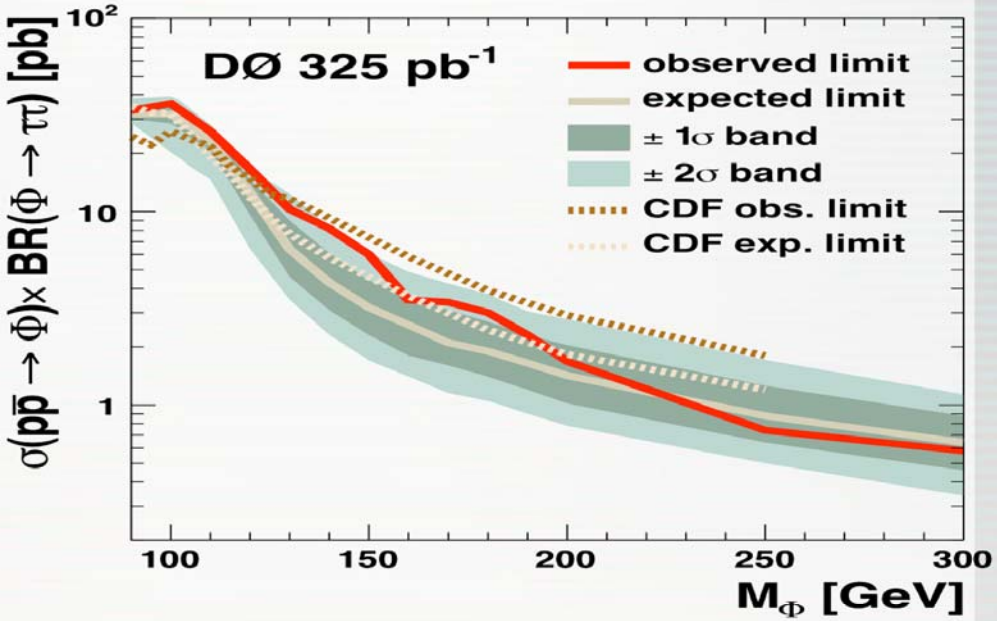


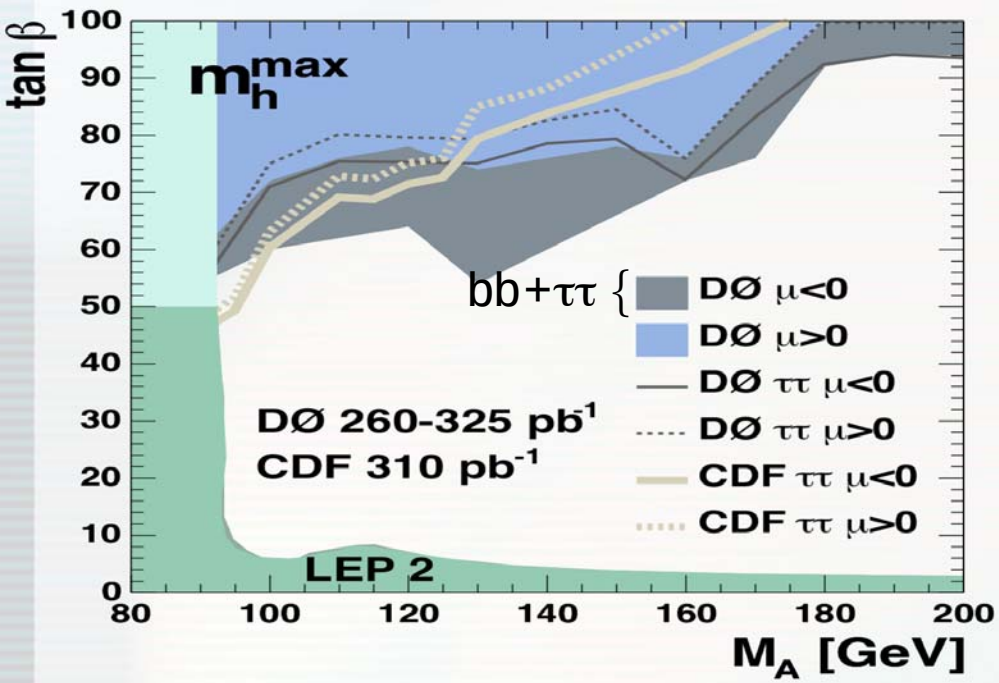
MSSM Higgs→ττ

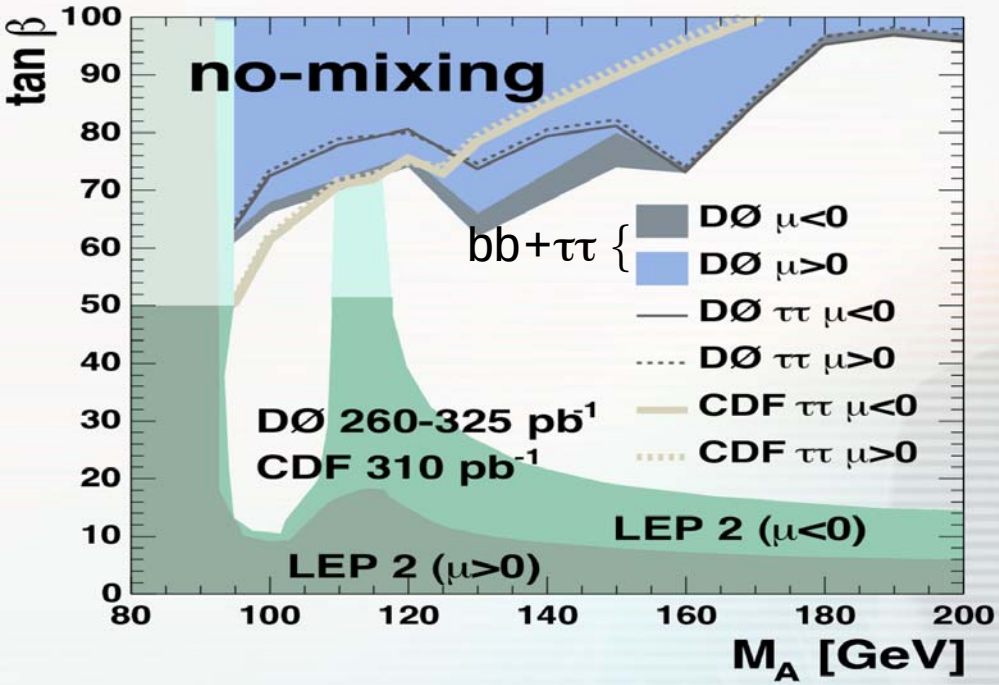
D0 Collaboration, hep-ex/0605009 (2006)

Use similar technique as CDF, add $\tau_e\tau_\mu$ channel







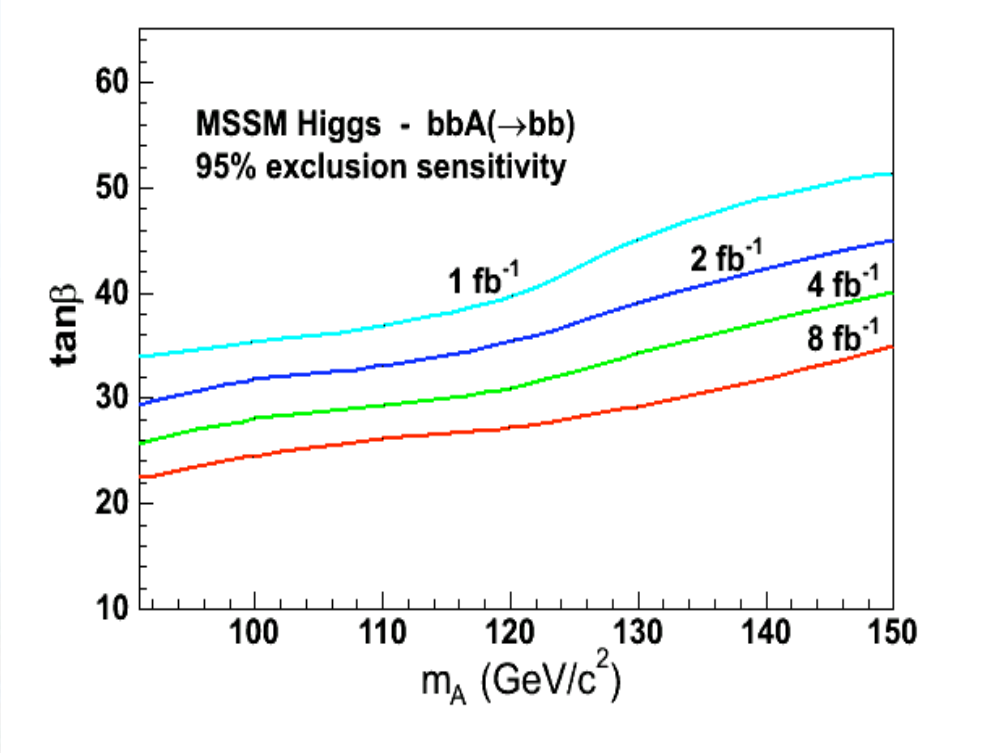


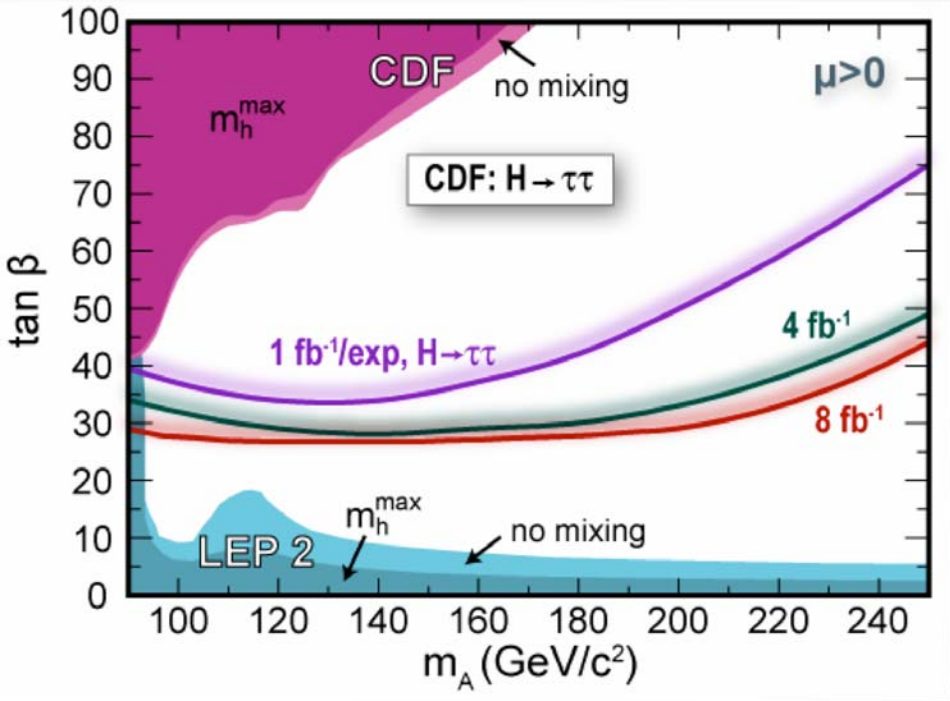
Outlook for MSSM Higgs at the Tevatron

Projections for neutral MSSM Higgs reach, 95% CL exclusion

Assumptions:

- similar CDF/D0 sensitivity
- some acceptance increase for $\tau\tau$
- techniques are kept the same (conservative), hope to do better





CDF and D0 can effectively probe low-mass MSSM Higgs

… and in the next couple of months we have to make good on the 1fb^{-1}/exp promise

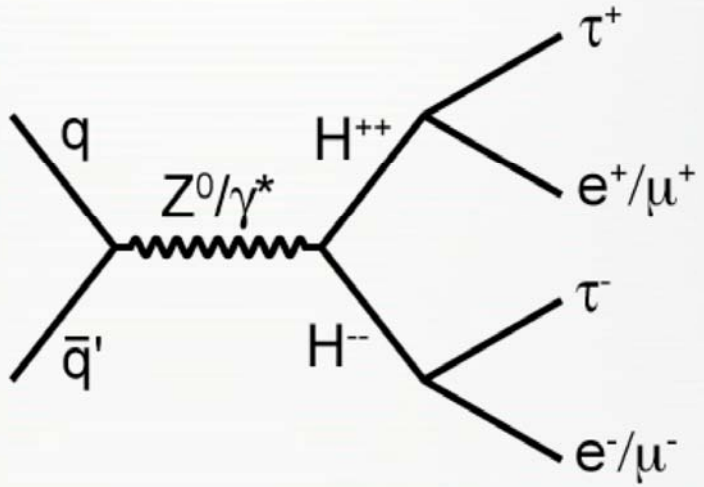
Search for $H^{++/--} \to e\tau, \mu\tau$

DY-like $H^{++}H^{--}$ pair production

Published CDF results in e/μ channels

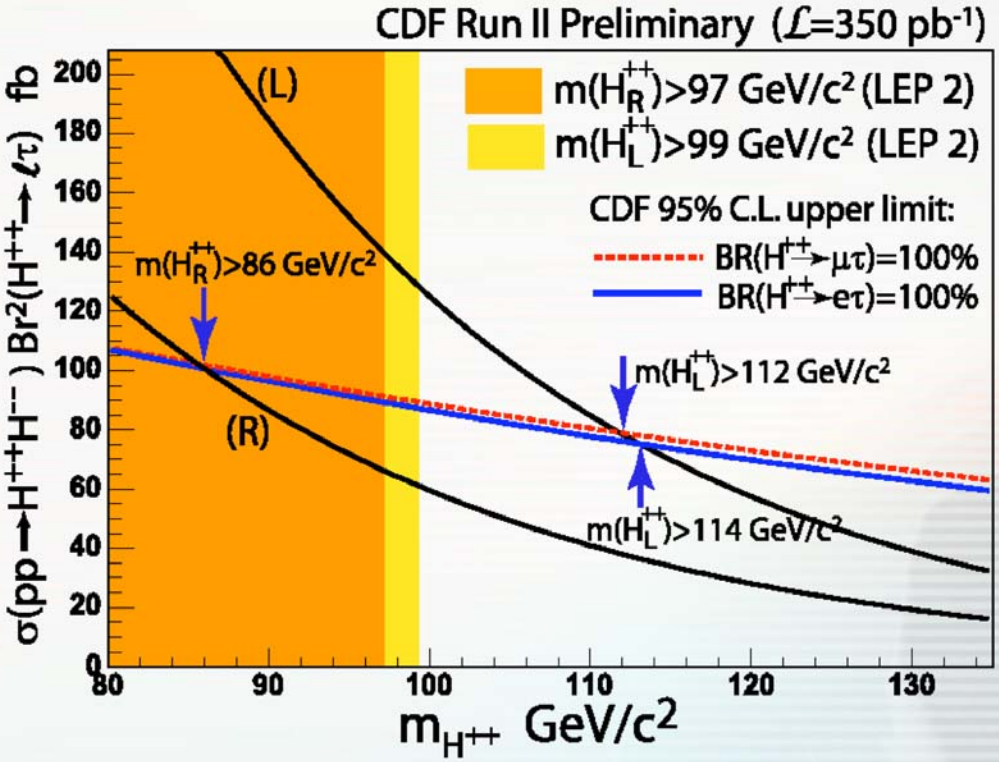
CDF Collaboration, PRL 93, 221802 (2004)

supersede the LEP limits



- $H^{++/--} \to e\tau, \mu\tau$ event selection:
  - Electron/muon p_T>20 GeV
  - Tau p_T>15 GeV
  - Isolated lepton candidate (ILC) w/ track p_T>10 GeV
- Two event categories: 3ℓ, 4ℓ
- Dominant backgrounds:
  - Z→ee/μμ+jets, ZZ, Multi-jet
    - Require large scalar sum of E_T of the decay products
    - Veto on opposite sign same-flavor leptons with $m_{\ell\ell}$<30 GeV, or 71<$m_{\ell\ell}$<111 GeV

Expect N_{bg}=0.3 (0.4) for the eτ (μτ), observed 0 events



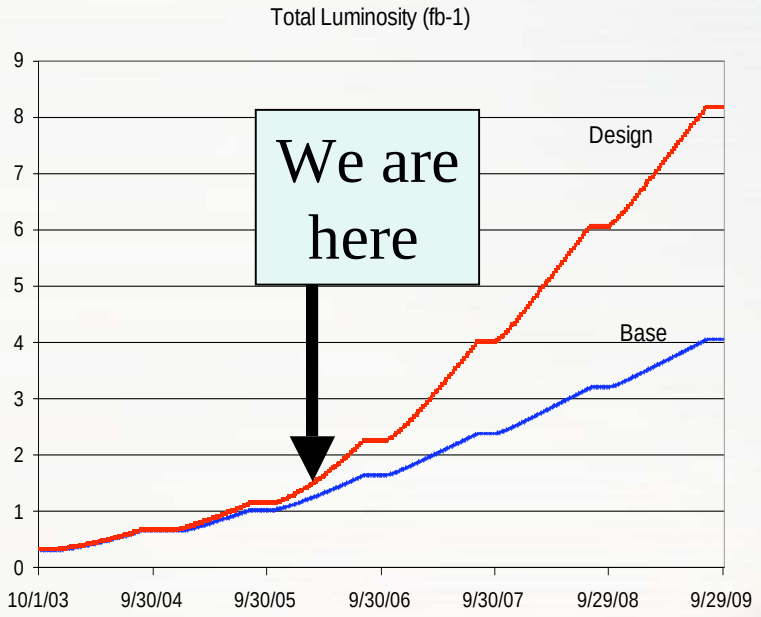
Summary

- **All major Higgs search channels are being explored by CDF and D0**
- **New/updated results with 1 fb^{-1} of data will become available over the summer**
- **Combine CDF and D0 results!**

- **In the longer term:**
  - **Use improved analysis techniques**
  - **Take advantage of the larger data samples**

Expect by 2009 to collect:
- 4 fb^{-1}/exp (pessimistic scenario)
- 8 fb^{-1}/exp (optimistic scenario)

Most of the data is ahead of us!



Over the next couple of years the Tevatron has a potential to:
- **Observe/rule out SM Higgs in some regions below 180 GeV**
- **Observe light MSSM Higgs, or constrain the SUSY parameter space**